



## UNITED STATES AIR FORCE AFIOH

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# Bioenvironmental Engineer's Guide to Ionizing Radiation

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9700 Avenue G, Southeast  
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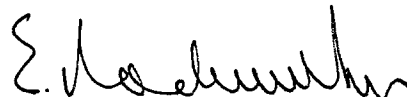

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## List of Acronyms

AAPM	American Association of Physicists in Medicine
AEA	Atomic Energy Act
AF	Air Force
ANG	Air National Guard
AFI	Air Force Instruction
AFIOH	Air Force Institute for Operational Health
Bkgd	Background
Bq	Becquerel
CF	correction factor
CFR	Code of Federal Regulations
Ci	Curie
DandD	Decontamination and Decommissioning
DoD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
DU	depleted uranium
<sup>En</sup> U	Uranium enriched in <sup>235</sup> U isotope
EPA	Environmental Protection Agency
Gy	gray
HEU	highly enriched uranium
ICRP	International Commission on Radiological Protection
kVp	kilovolts peak

LINAC	Linear Accelerator
mA	milliAmperes
NARM	naturally-occurring and accelerator-produced radioactive material (NARM)
NAS	National Academy of Sciences
<sup>Nat</sup> U	Uranium with naturally-occurring composition of uranium isotopes
NCRP	National Council on Radiation Protection and Measurements
NDI	non-destructive inspection
NESHAPS	National Emission Standard for Hazardous Air Pollutants
NRC	Nuclear Regulatory Commission
Q	quality factor (Nuclear Regulatory Commission)
QF	quality factor (other documents)
rad	radiation absorbed dose
RAM	radioactive material
RFR	radio frequency radiation
RIC	Radioisotope Committee
RTG	radioisotope thermal generator
SDR	Radiation Surveillance Division
SDWA	Safe Drinking Water Act
SF	spontaneous fission
SI	System International
STANAG	Standardization Agreement
TI	Transport Index
TLD	thermoluminescent dosimetry



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## **BIOENVIRONMENTAL ENGINEER'S GUIDE TO IONIZING RADIATION**

### **1. Introduction**

This report provides Bioenvironmental Engineering Services (BES) personnel with guidance on measurement and hazard assessments of ionizing radiation found in common Air Force (AF) operations. Due to some parallel requirements, this report may also be useful to other career fields/teams (e.g., Civil Engineering Readiness, medical, fire) that have responsibility for radiation safety programs, and as a reference for health physicists. Proper instrument selection and use is a primary focus. As such the bulk of the report is organized according to the different measurement tasks encountered by BES.

Background information on radiation detection systems, detection efficiencies, and radionuclides common to Air Force operations is provided as an aid. While focussed primarily on measurements, some support information on regulatory limits and laboratory analyses is provided and referenced. More complete regulatory requirements can be found in Air Force Instructions 40-201, "Management of Radioactive Materials in the Air Force" and 48-148, "Ionizing Radiation Protection," and Titles 10 (Energy), 29 (Occupational Safety and Health Administration [OSHA]), 49 (Transportation) Code of Federal Regulations (CFR).

The report is expected to encompass the vast majority of radiation safety and measurement tasks encountered by BES. For brevity's sake, the report has practical limits; additional information and questions regarding unique measurements and other radiation protection issues should be addressed to the Consulting Branch, Radiation Surveillance Division of the Air Force Institute for Operational Health (AFIOH/SDR).

## 2. Ionizing Radiation Hazard Management

a. General. Radiation hazard management accomplished for AF operations is very similar to the methodology accomplished for other types of workplace and deployment hazards like noise, chemicals, etc. The primary differences between radiation hazard evaluations and others are in the applicable standards and regulations, and tools used to measure/assess the hazards. As such, this guide will provide more details in the aspects of radiation hazard management that are unique to radiation. Figure 2-1 provides an overview of the management process.

b. Standard/Regulatory Requirements.

(1) AF Instructions. There are a multitude of standards and regulatory requirements that are applicable to radiation exposure scenarios. For radioactive material (RAM) use in the AF, AFI 40-201, "Managing Radioactive Material in the US Air Force," is applicable to Nuclear Regulatory Commission (NRC) licensed materials, and naturally-occurring radioactive material (NORM) and accelerator-produced RAM. Exposures to nuclear weapons related materials are generally governed by AFI 91-108, "Air Force Nuclear Weapons Intrinsic Radiation Protection Program." Exposures to machine-generated ionizing radiation and uncontrolled radiation sources like radon gas are governed by AFI 48-148, "Ionizing Radiation Protection."

(2) Federal Regulations. Radiation protection practices for NRC-licensed materials must follow NRC rules. Thus, AFI 40-201 largely references NRC rules for AF RAM management. For non-NRC licensed materials, like nuclear weapons related materials referenced in Section 91b of the Atomic Energy Act of 1954 and NARM, AFI 40-201 and AFI 91-108 generally follow NRC rules for personnel exposures and exposures to members of the general public. For similar exposures to machine-generated ionizing radiation, AFI 48-148 is consistent with NRC rules, which generally also ensures that OSHA requirements are met. Within this AFI, radon exposure policy for members of the general public and workplace members is consistent with the Environmental Protection Agency's (EPA) recommendations. Department of Transportation (DOT) rules are followed for transport of RAM, except for nuclear weapons related materials. The EPA has a number of rules that may impact AF operations. The important ones that impact BES are the Safe Drinking Water Act (SDWA) and the National Emission Standard for Hazardous Air Pollutants (NESHAPS).

(3) State Regulations. Because most active AF installations have exclusive federal jurisdiction, state regulations will not apply to ionizing radiation exposures. For some active and many Air National Guard (ANG) installations, state regulations may apply. For NRC-licensed RAM, agreement states will have rules consistent with NRCs, while non-agreement states defer to NRC rules. Some states will have separate rules for NARM and machine-generated radiations, but most regulations are generally consistent with NRC rules for exposures to personnel and the general public. Review of federal jurisdiction status and existing state regulations should be made for all installations.

(4) Guidance Documents. There are many guidance documents that may be recommended or mandated for use in AF radiation protection programs. The National Council on Radiation Protection and Measurements (NCRP) has an extensive collection of reports that are applicable to all aspects of radiation protection; AFI 48-148 extensively references many of these reports. The

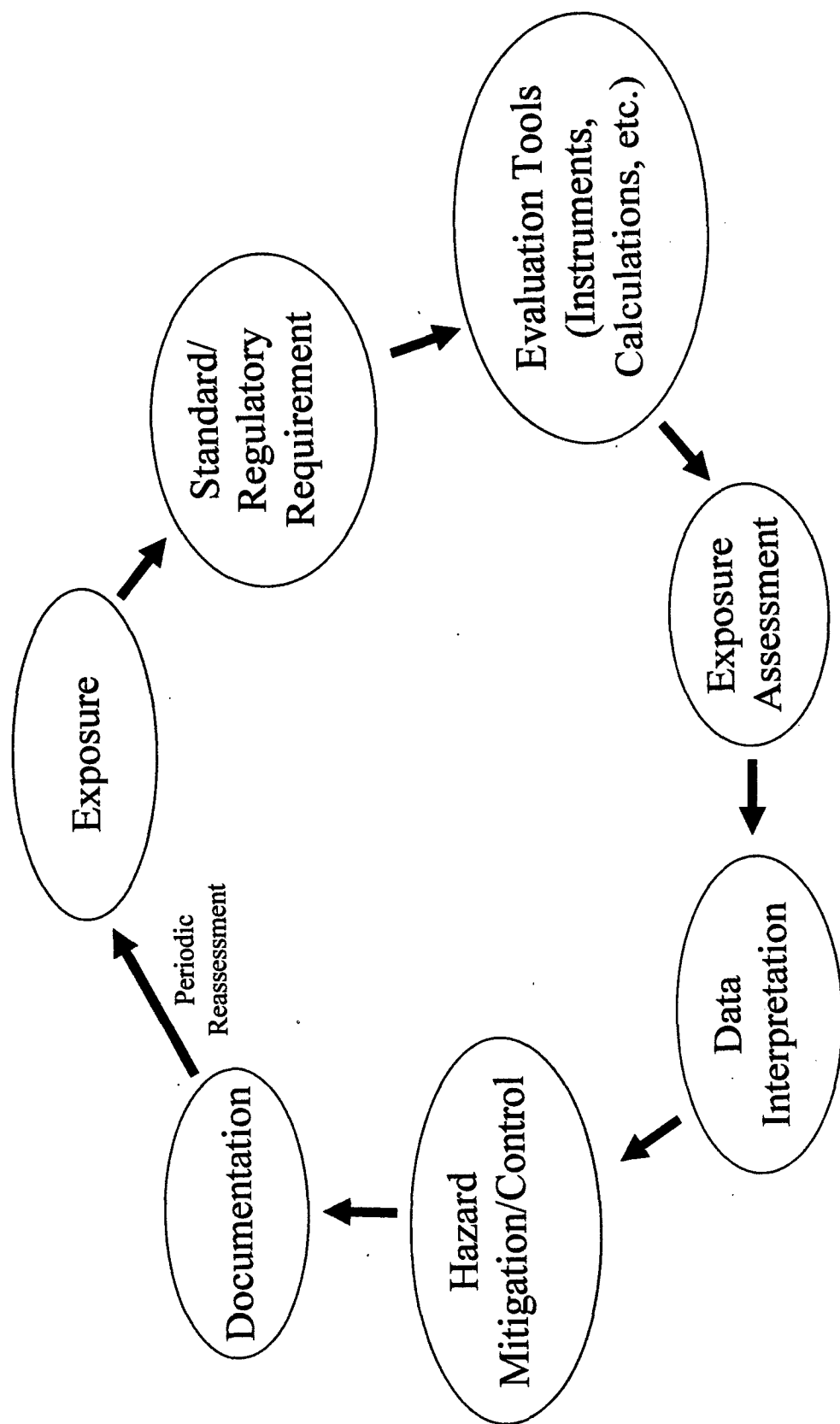


Figure 2-1. Hazard Evaluation Process.

International Commission on Radiological Protection (ICRP), American Association of Physicists in Medicine (AAPM), and National Academy of Sciences (NAS) reports are implemented in AF radiation protection programs. The US Army Center for Health Promotion and Preventive Medicine (USACHPPM) published Technical Guide 244, "The Medical NBC Battlebook," that has useful radiation safety information

c. Evaluation Tools, Exposure Assessment, and Data Interpretation. The tools used to evaluate radiation exposure commonly involve portable radiation detection instrumentation, passive dosimetry monitoring for area surveys, passive and active personnel monitoring, computer-modelling codes, calculations, and laboratory analysis. Most exposure scenarios evaluated by BES involve the use of portable instrument measurements. Questions concerning the use of portable instruments for measurements, details on assessment tasks, and data interpretation are common among BES. Therefore, these aspects of hazard evaluations will be emphasized.

d. Hazard Mitigation/Control. Hazard mitigation/control is an important aspect of the overall process of radiation hazard management. Many of the mitigation/control techniques are similar to those applied to other hazards in the workplace. Administrative controls may include access control, caution/warning signs and postings, alarms, education/training, personnel protective devices, locks, etc. Engineering controls may include shielding, shutter interlocks, ventilation, etc. In general, implementation of mitigation/controls is common to BES operations – some details will be provided in individual parts of Section 6, where appropriate.

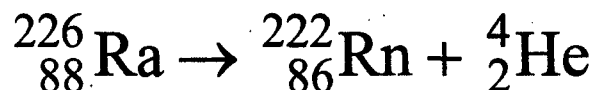
e. Documentation. Document preparation (and its retention) is an important aspect of ionizing radiation hazard management. BES is very accustomed to documentation of hazard management in AF workplaces. Thus, emphasis will only be provided for requirements more unique to radiation protection like retention of instrument calibration certificates, exposure assessment frequency, and document retention.

### 3. Ionizing Radiation Types, Characteristics, and Common Air Force Sources

a. General. Ionizing radiation sources are common to many AF operations being used in medical diagnostics and therapy; non-destructive inspection of aircraft parts and baggage; security forces; AF research operations; electronics systems vulnerability testing; hazardous compound testing; and others. The sources fit into one of two categories: RAM and machine-generated. From a practical standpoint, radiation protection management is very similar for both sources. The primary differences in management reside in different regulatory entities and the fact that RAM must be controlled during non-use periods and has long-term management responsibility for long-lived isotopes.

#### b. Ionizing Radiation Types and Characteristics.

(1) Alpha ( $\alpha$ ) Particle Radiation.  $\alpha$ -particle decay is one of the four basic decay mechanisms for RAM and normally occurs in isotopes with atomic number greater than 83 (bismuth).  $\alpha$ -particles are energetic helium nuclei and are characterized by their kinetic energy. The kinetic energy of  $\alpha$ -particle emissions is discrete for individual isotopes. The example below is for Ra-226, with representative kinetic energies of common AF  $\alpha$ -particle emitting isotopes in Table 3-1. From data in the table, it is apparent that many of the common  $\alpha$ -particle emissions have kinetic energies



Equation 3-1

TABLE 3-1. Kinetic Energy of  $\alpha$ -Particle Emissions for Isotopes Common to AF Operations.

Isotope	Kinetic Energy (MeV)	Isotope	Kinetic Energy (MeV)
Ra-226 ( $t_{1/2}$ : 1600 y)	4.78 (94 %)	Pu-239 ( $t_{1/2}$ : $2.4 \times 10^4$ y)	5.15 (88 %)
	4.60 (6 %)		5.11 (12 %)
Po-218 ( $t_{1/2}$ : 3.1 min)	6.00 (100 %)	U-238 ( $t_{1/2}$ : $4.5 \times 10^9$ y)	4.20 (79 %)
U-234 ( $t_{1/2}$ : $2.5 \times 10^5$ y)	4.78 (72 %)	Th-232 ( $t_{1/2}$ : $1.4 \times 10^{10}$ y)	4.15 (21 %)
	4.72 (28 %)		4.01 (78 %)
Th-230 ( $t_{1/2}$ : $7.5 \times 10^4$ y)	4.69 (76 %)	U-235 ( $t_{1/2}$ : $7.0 \times 10^8$ y)	3.95 (22 %)
	4.62 (24 %)		4.40 (55 %)
Am-241 ( $t_{1/2}$ : 432 y)	5.49 (85 %)		4.37 (17 %)
	5.44 (13 %)		4.22 (6.6 %)
	5.39 (2 %)		4.32 (4.4 %)
			4.56 (4.2 %)
			4.41 (2.1 %)
			Others (10.7 %)

between 4 and 5.5 MeV. It is important to note that in the decay for these isotopes other types of radiation emissions occur like gamma ( $\gamma$ )- and x-rays. Also, other emissions occur from the subsequent decay of radioactive daughter products. Among radiation types,  $\alpha$ -particles have a very limited penetration range in materials. Due to this, the emissions do not present an external radiation hazards, and  $\alpha$ -particle emitting RAM must be internally deposited for  $\alpha$ -particle emissions to present any radiation dose. Table 3-2 lists the penetration range of some  $\alpha$ -particles in air and water. Due to the limited range of  $\alpha$ -particles in air, portable detection instrumentation must be in close proximity to the source of emission for adequate detection. A thin film of cover will completely absorb the particles, precluding detection. Alpha particles with energies typical for RAM emissions cannot penetrate a thin sheet of paper.

TABLE 3-2. Penetration Range of  $\alpha$ -Particles in Air and Water.

Radionuclide	Alpha Particle Energy (MeV)	Range in Air [STP] (cm)	Range in Water ( $\mu\text{m}$ )
Th-232	4.00	2.4	30
Pu-239	5.15	3.7	42
Po-218	6.00	4.6	53

(2) Beta ( $\beta$ ) Particle Radiations. Beta particle decay is one basic decay mechanisms for RAM and occurs in isotopes across the spectrum of atomic number from the lowest to the very high. Beta particles are highly energetic negatively charged electrons. Figure 3-1 illustrates the decay and  $\beta$ -emission of tritium ( $^3\text{H}$ ). Like  $\alpha$ -emissions,  $\beta$ -particles are characterized by their kinetic energy, but are not emitted discretely and have a range of potential kinetic energies. Figure 3-2 provides an example of a typical energy spectrum. A good rule of thumb for  $\beta$ -particle emissions is the average kinetic energy is approximately one-third of its maximum energy. In general,  $\beta$ -particles are more penetrating than  $\alpha$ -particles in materials. Table 3-3 lists the penetration range of several  $\beta$ -particles in air, water, and aluminum. For the low-energy  $\beta$ -particles, penetration is similar to  $\alpha$ -particles in and is limited to a few centimeters in air and tens of micrometers ( $\mu\text{m}$ ) in water. As such, these emissions do not present external radiation hazards and the RAM must be internally deposited for these  $\beta$ -particle emissions to present any radiation dose. For the medium- and high-energy  $\beta$ -particle emitters like  $^{137}\text{Cs}$  and  $^{90}\text{Y}$ , penetration is significant in air and in water. In contrast to lower energy  $\beta$ -particles, these can present external radiation hazards. However, a few millimeters of aluminum or a centimeter of plastic will effectively absorb all of the  $\beta$ -particles. Since the production rate of bremsstrahlung x-rays is high when high-energy  $\beta$ -particles interact in high-Z materials, low-Z materials like plastics are preferred for shielding.

(3) Positron Particle Decay. Positron particles emission is one of the four basic decay mechanisms. Positrons are positively-charged electrons with this mode of decay being the opposite of  $\beta$ -particle decay. In general, positrons have virtually the same penetration range as electrons, but are annihilated when they collide with an electron, producing two 511 keV photons. Beyond small



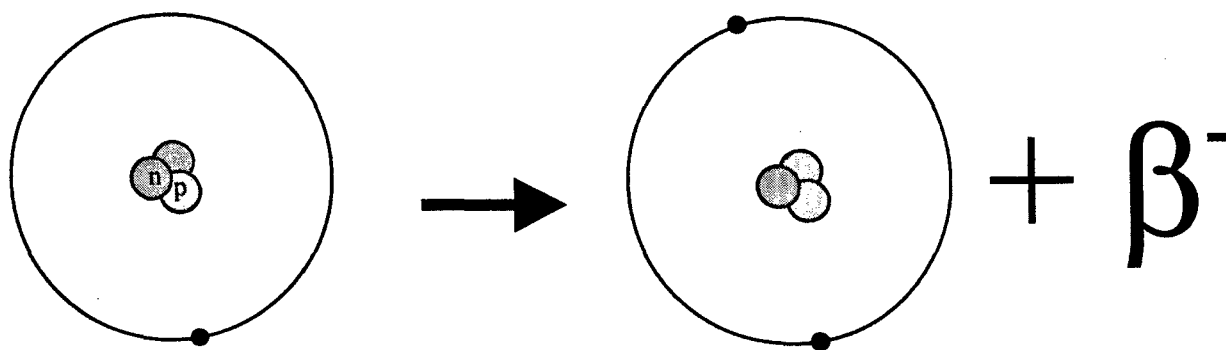


Figure 3-1. Radioactive Decay of Tritium ( ${}^3\text{H}$  or  $\text{H-3}$ ) into  $\text{He-3}$ .

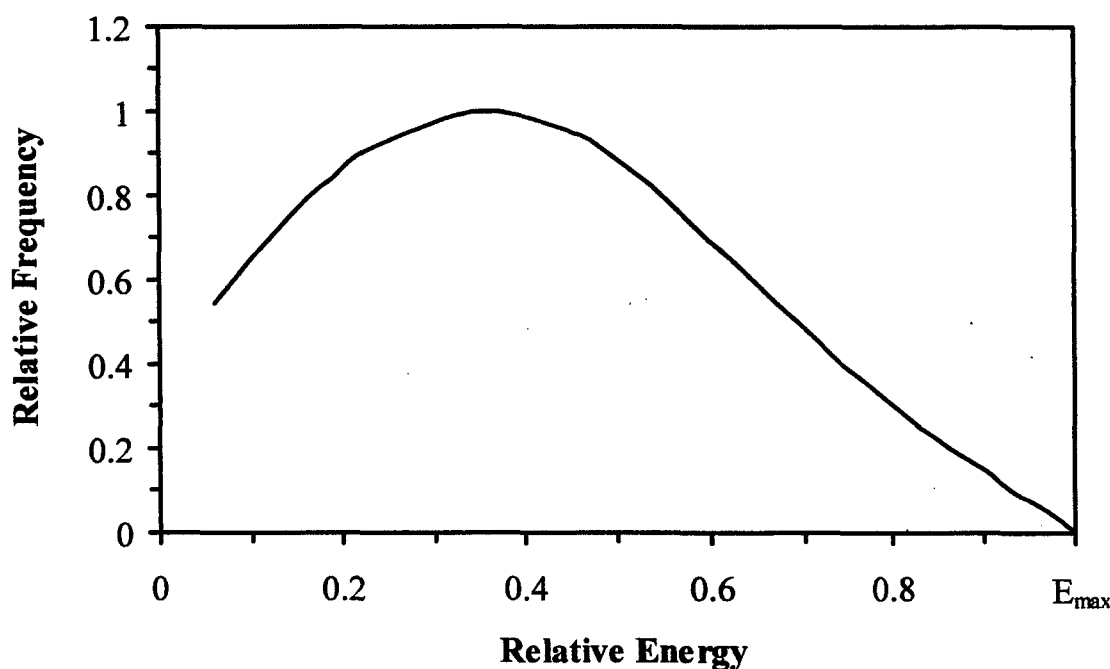


Figure 3-2. Energy Spectrum of Typical Beta Particle Emission.

check sources and accelerator-produced isotopes, the only positron emitter used in the AF is  ${}^{18}\text{F}$  (nuclear medicine) and is beyond the scope of this guide.

(4) **Electron-Capture Decay.** Electron-capture decay is one of the four basic decay mechanisms. In this decay mode, the nucleus undergoes decay by capturing an orbital electron, which reduces the atomic number of the nucleus by one. The decay produces the same daughter nucleus as that of positron emission decay. For some radionuclides, electron-capture and positron particle are competitive decay mechanisms. Table 3-4 contains some example radionuclides used in the AF that decay by electron-capture decay.

TABLE 3-3. Penetration Range of Beta Particles in Air, Water, and Aluminum.

Radionuclide	Maximum Beta Particle Energy (keV)	Range in Air [STP] (cm)	Range in Water (cm)	Range in Aluminum (mm)
H-3 ( $t_{1/2}$ : 12.3 y)	19	0.5	0.0006 (6 $\mu$ m)	< 0.001
Ni-63 ( $t_{1/2}$ : 100 y)	66	4.9	0.006 (60 $\mu$ m)	< 0.01
C-14 ( $t_{1/2}$ : 5730 y)	156	26	0.03 (300 $\mu$ m)	0.1
Cs-137 ( $t_{1/2}$ : 30 y)	510	120	0.16	0.5
Y-90 ( $t_{1/2}$ : 64 h)	2300	850	1.1	4.5

(5) Other Sources of Electrons (Linear Accelerators). There are many other sources of electrons in AF operations. RAM undergoing radioactive decay can emit electrons of discrete energy when energy from the nucleus is transferred to an orbital electron. More important, however, are linear accelerators (LINAC) used for radiation effects on materials testing and radiation therapy. Dependent on the application, both types of device produce electrons typically with energies of a few to 35 MeV. The primary beam from accelerators presents the greatest source of radiation, but is accompanied by secondary emissions that are produced from interactions of electrons with beamline components. For some LINACs, x-rays are intentionally produced by placing targets (usually tungsten) in the beam or through interactions incidental to operation. The production of high-energy Bremsstrahlung x-rays presents the need for shielding of different construction than that for  $\beta$ -radiation alone and promotes the production of neutrons (through photonuclear interactions) if photon energies exceed 10 MeV. In turn, neutrons have unique shielding considerations. Like photonuclear interactions, neutrons activate materials that create external radiation fields when devices are not operating and require long-term RAM management responsibility.

#### (6) Photons.

(a) General. Photons are electromagnetic radiation that encompasses  $\gamma$ - and x-radiations emitted by RAM during radioactive decay,  $\gamma$ -radiations from nuclear interactions, and x-radiations from electron interactions with materials. Regardless of the emission source, photons are characterized by their energy and have the same radiation safety implications.

(b) Photons Emitted by RAM. Many radioactive materials that undergo  $\alpha$ -,  $\beta$ -, and positron particle decay emit  $\gamma$ -radiation from the nucleus with discrete energy. Characteristic x-radiation is also emitted when orbital electrons transition from one shell to another. Table 3-4 lists the photon emissions and radioactive decay mode of RAM in AF operations. In general, most of the RAM common to AF operations has some type of photon emission(s). These emissions require radiation protection attention in addition to that of the particulate emissions. Due to the discrete photon emission energies, isotopes with photon emissions are more easily identified in the laboratory

and field environments than those without. For the latter, more complex spectroscopy methods are necessary to determine the  $\alpha$ - and  $\beta$ -emitter. Some qualitative methods can be accomplished in the field, but quantitative methods are normally accomplished by laboratory analysis. Table 3-5 lists RAM in AF operations that do not have photon emissions. Detection of photon emissions is the most common method for identifying the presence of or locating RAM. Without them, the task is significantly more difficult, especially if particle emissions are self-absorbed in the RAM source.

### (c) Photon Emissions from Machines.

1 General. The AF has a multitude of machine-generated sources of photons. Virtually all are Bremsstrahlung x-rays, created from the purposeful bombardment of dense metallic targets with electrons or interactions coincidental with the production of electrons. Any machine that accelerates electrons across an electric potential of 10,000 volts (V) or greater can produce x-rays. X-ray energy spectral distributions are highly varied dependent on the source of electromotive potential (continuous or time-varying), target type, target thickness, location with respect to beam, filtration, and others. Typically, less than 1 % of the kinetic energy of electrons is converted into useful x-ray energy, with the rest into thermal energy. X-rays are emitted in a continuous distribution with discrete energy characteristic x-rays from orbital electron transitions. Figure 3-3 provides a generic spectrum for x-rays produced in a thin target by electrons of 100 keV. From the spectrum, it is apparent that the maximum x-ray energy is equal to the maximum electron energy, however, the majority of x-rays by frequency are of considerably lower energy. When thick targets are used, the energy distribution shifts to higher energies like that illustrated in the example of the figure. Further enhancements to thick target x-ray spectra can be made with the use of filters (i.e., metals added to the x-ray beamline). The figure provides an example of a filtered spectrum. Clear from the example is the shift in the relative x-ray spectrum to higher energies, which is termed "hardening." Many types of metals are used to filter x-ray beams like beryllium, aluminum, copper, tin, holmium, and tungsten. Dependent on the application, filtration can enhance image quality most commonly by restricting the range of x-ray energies. For medical applications, proper filter selection can improve image quality and reduce patient radiation dose.

2 Machines Used in Medicine. Low-energy x-ray machines are used primarily for diagnostic purposes in medical and dental clinics. Diagnostic machines are generally used for fixed, short-pulse duration procedures (conventional) and fluoroscopy, where the exposure duration is controlled real-time by an operator. For most machines used in the medical and dental clinics, the tube electric potential is between 50 and 150 kVp. For mammography machines, tube electric potential is typically between 25 and 45 kVp, dependent on the target material and image receptor. In diagnostic equipment, filtration is a critical component that reduces the radiation exposure to the patient of x-ray energies that provide no useful diagnostic benefit. Higher energy x-ray machines and x-rays produced from dual-purpose linear accelerators (i.e., emit x-rays or electrons) may be used for diagnostic procedures or radiation therapy. The peak x-ray energies typically are in the range of a few to about 25 MeV.

3 Industrial X-Ray (Non-Destructive Inspection) Machines. X-ray machines used in non-destructive inspection (NDI) are the most common type of x-ray machine in the AF, outside of the clinic. Table 3-5 lists some of the more frequently used industrial x-ray units. The units and specifications are generic and may not be representative of units that have been modified or updated.

TABLE 3-4. Photon Emissions and Radioactive Decay Mode for RAM in AF Operations.

Radioisotope	Decay Mode	Significant Photon Emission Energy (keV), Frequency, and Type	Use
F-18 ( $t_{1/2}$ : 110 min)	Positr. (97 %) Electron Capture (3%)	511 (194 %) - $\gamma$ oxygen x-rays	Nuclear Medicine
Na-24 ( $t_{1/2}$ : 15 h)	Beta	1.369 (100 %) - $\gamma$ 2.754 (100 %) - $\gamma$	Neutron Activation Product of Na-23
Fe-55 ( $t_{1/2}$ : 2.7 y)	Electron Capture	manganese x-rays	X-ray Fluorescence Devices
Co-57 ( $t_{1/2}$ : 272 days)	Electron Capture	122 (87 %) - $\gamma$ 136 (11 %) - $\gamma$ iron x-rays	X-ray Fluorescence, Some Generally-Licensed Devices
Co-60 ( $t_{1/2}$ : 5.3 y)	Beta	1,173 (100 %) - $\gamma$ 1,332 (100 %) - $\gamma$	Check Sources, Irradiators, Industrial Radiography
Ga-67 ( $t_{1/2}$ : 3.3 days)	Electron Capture	93 (40 %) - $\gamma$ 184 (24 %) - $\gamma$ 296 (22 %) - $\gamma$ 388 (7 %) - $\gamma$	Nuclear Medicine
Kr-85 ( $t_{1/2}$ : 10.8 y)	Beta	514 (0.41 %) - $\gamma$	Check Sources, Gauges, Exciter Circuits
Mo-99 ( $t_{1/2}$ : 66 h)	Beta	181 (7 %) - $\gamma$ 740 (12 %) - $\gamma$ 780 (4 %) - $\gamma$	Nuclear Medicine
Tc-99m ( $t_{1/2}$ : 6 h)	Internal Transition	140 (90 %) - $\gamma$ technetium x-rays	Nuclear Medicine
Pd-103 ( $t_{1/2}$ : 17 days)	Electron Capture	rhodium x-rays	Nuclear Medicine
Cd-109 ( $t_{1/2}$ : 1.26 y)	Electron Capture	88 (12 %) - $\gamma$ silver x-rays	X-ray Fluorescence, Lead-Based Paint Analyzers
In-111 ( $t_{1/2}$ : 2.8 days)	Electron Capture	173 (89 %) - $\gamma$ 247 (94 %) - $\gamma$	Nuclear Medicine
I-123 ( $t_{1/2}$ : 13 h)	Electron Capture	159 (83 %) - $\gamma$	Nuclear Medicine
I-125 ( $t_{1/2}$ : 59.4 days)	Electron Capture	35 (7 %) - $\gamma$ tellurium x-rays	Nuclear Medicine
I-131 ( $t_{1/2}$ : 8 days)	Beta	284 (5 %) - $\gamma$ 364 (82 %) - $\gamma$ 637 (7 %) - $\gamma$	Nuclear Medicine
Xe-133 ( $t_{1/2}$ : 5.2 days)	Beta	81 (37 %) - $\gamma$	Nuclear Medicine

TABLE 3-4. Photon Emissions and Radioactive Decay Mode for RAM in AF Operations (cont.).

Radioisotope	Decay Mode	Significant Photon Emission Energy (keV), Frequency, and Type	Use
Cs-137 ( $t_{1/2}$ : 30 y)	Beta	662 (85 %) - $\gamma$ barium x-rays	Check Sources, Industrial Radiography, Calibration, Exciter Circuits, Irradiators
Ir-192 ( $t_{1/2}$ : 74 days)	Beta (95.5 %)  Electron Capture (4.5 %)	296 (29 %) - $\gamma$ 308 (30 %) - $\gamma$ 317 (81 %) - $\gamma$ 468 (49 %) - $\gamma$ 589 (4 %) - $\gamma$ 604 (9 %) - $\gamma$ 612 (6 %) - $\gamma$	Industrial Radiography
Tl-201 ( $t_{1/2}$ : 73 h)	Electron Capture	135 (2 %) - $\gamma$ 167 (8 %) - $\gamma$ mercury x-rays	Nuclear Medicine
Ra-226 ( $t_{1/2}$ : 1600 y)	Alpha	186 (4 %) - $\gamma$ radon x-rays photons from daughters: Rn-222, Po-218, Pb-214, Bi-214, Po-214	Luminous Products, Neutron Sources (w/ Be)
Th-230 ( $t_{1/2}$ : $7.5 \times 10^4$ y)	Alpha	68 (0.4 %) - $\gamma$ radium x-rays	Check Sources
Th-232 ( $t_{1/2}$ : $1.4 \times 10^{10}$ y)	Alpha	radium x-rays photons from daughters: Ra-228, Ac-228, Th-228, Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Tl-208	Magnesium-Thorium Alloy (Aircraft Engine Parts, Missile Skins), Thoriated Glass Coatings, Check Sources
U-234 ( $t_{1/2}$ : $2.5 \times 10^5$ y)	Alpha	thorium x-rays	30 mm Ammunition, Nuclear Weapons, Counterweights
U-235 ( $t_{1/2}$ : $7.0 \times 10^8$ y)	Alpha	143 (11 %) - $\gamma$ 185 (57 %) - $\gamma$ thorium x-rays	30 mm Ammunition, Nuclear Weapons, Counterweights, Calibration
U-238 ( $t_{1/2}$ : $4.5 \times 10^9$ y)	Alpha	thorium x-rays photons from daughters: Th-234, Pa-234m	30 mm Ammunition, Nuclear Weapons, Counterweights
Pu-238 ( $t_{1/2}$ : 88 y)	Alpha	uranium x-rays	Radioisotope Thermoelectric Generators
Pu-239 ( $t_{1/2}$ : $2.4 \times 10^4$ y)	Alpha	uranium x-rays	Nuclear Weapons, Neutron Sources (w/ Be), Calibration
Am-241 ( $t_{1/2}$ : 432 y)	Alpha	60 (36 %) - $\gamma$ neptunium x-rays	Static Eliminators, Chemical Agent Detectors, Neutron Sources (w/ Be)

TABLE 3-5. RAM in AF Operations Without Photon Emissions.

Radioisotope	Decay Mode	Particle Energy (keV)	Use
H-3 ( $t_{1/2}$ : 12.3 y)	Beta	19 (maximum)	Exit Signs, Biological Research, Nuclear Weapons, Luminous Products
C-14 ( $t_{1/2}$ : 5730 y)	Beta	156 (maximum)	Astroinertial Navigation Devices, Biological Research
P-32 ( $t_{1/2}$ : 14.3 days)	Beta	1,710 (maximum)	Biological Research
Ni-63 ( $t_{1/2}$ : 100 y)	Beta	66 (maximum)	Ionscans, Chemical Agent Monitors/Alarms, Gas Chromatographs
Sr-90/Y-90 ( $t_{1/2}$ : 29 y)	Beta	546/2,270 (maximum)	In-flight Blade Inspection Systems (IBIS), Ice Detectors, Radioisotope Thermoelectric Generators, Calibration
Pm-147 ( $t_{1/2}$ : 2.6 y)	Beta	224 (maximum)	Luminous Products, Electron Tubes
Re-187 ( $t_{1/2}$ : $4.4 \times 10^{10}$ y)	Beta	3 (maximum)	Electron Tubes
Po-210 ( $t_{1/2}$ : 138 days)	Alpha	5,305	Static Eliminators, Calibration, Neutron Sources

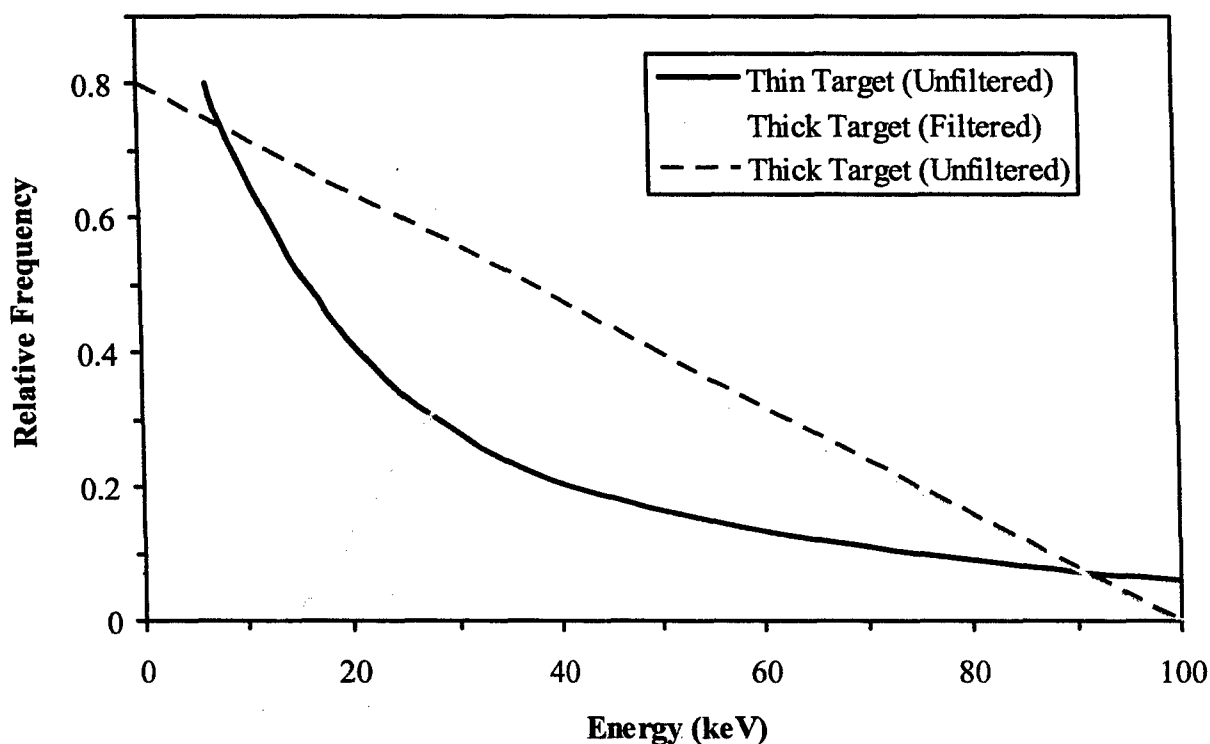


Figure 3-3. Generic Photon Energy Spectra of 100 kVp X-Ray Machine for Thin Target, Thick Target (Unfiltered), and Thick Target (Filtered).

From the table, generally these units use higher peak electric potential than that of common medical diagnostic x-ray units, and have significantly less beam filtration, because there is no need to reduce a patient dose. These units are also operated in continuous mode, rather than single pulse mode of conventional medical diagnostic x-ray units. In 1996, Armstrong Laboratory (Montgomery 1997) evaluated the hazards of the Golden Engineering 200 x-ray source planned for use in NDI operations. In general, for an individual inspection, scattered exposure rates were considerably lower than that of the LORAD LPX-160A.

TABLE 3-6. Typical Industrial X-Ray Equipment of NDI.

Model	Electric Potential Maximum (kVp)	Maximum Beam Current (mA)	Filtration (mm)	Dose Rate @ 1 meter (rem/min)
Lorad LPX-160A	160	5	1.6 (Be)	14
Magnaflux GXR7.6C	150	7	0.8 (Be)	49
Sperry SPX 160- KVP	160	5	2.3 (Be)	60
Sperry 275-KVP	275	10	0.1 Al Eq. (Be)	150
Sperry 300-KVP	300	10	2.4 (Be)	117

4 Research/Laboratory Related X-Ray Machines. The AF has a significant number of machines that produce x-rays in the research and laboratory environments. Among the more significant sources in terms of exposure potential are the sources used to test the radiation effects on materials, most commonly electronic components being tested for radiation vulnerability. High radiation exposure over prolonged periods is often produced by radioisotope irradiators. However, extremely high radiation fields over very short periods of time are usually produced by high power flash x-ray systems. Most of these devices use electrons with peak energy between a few to 10 MeV. Low-power x-ray systems may be used in laboratory settings for analytical procedures like x-ray fluorescence. These devices, in general, are low hazard.

5 Baggage Inspection and Other Systems. Baggage inspection systems are common to AMC terminals and other organizations that must perform security screens of hand-carried bags. X-ray systems used in AF operations are similar to those common to airport security inspection systems. Most systems have a conveyor belt that transports items intended for inspection under an x-ray beam that is directed downward. The systems typically operate at about 150 kVp. AF Office of Special Investigation (OSI) and Explosive Ordinance Disposal (EOD) organizations use portable x-ray machines periodically. These devices are low hazard, unless in the main beam.

6 X-Ray Generation Incidental to High Electric Potential Equipment. There are some AF devices that produce photons incidental to operation. Among the most important devices due to the high energy and frequency of use are electron particle accelerators used in medicine and radiation effects on materials testing. The range of electron energies for these devices is typically between a few and 35 MeV. All of these devices produce Bremsstrahlung and characteristic x-rays, and prompt  $\gamma$ -radiation. For accelerator energies above 10 MeV, neutron production is an important

consideration and the activation-produced RAM that has delayed radiation emissions. Long-lived RAM may include some of the isotopes listed in Table 3-7, with isotopes being dependent on beam energy, materials in proximity to the beam, and target materials. For these devices, a health physicist's evaluation should be made.

TABLE 3-7. Example Long-Lived RAM Produced in LINACS with Energy > 10 MeV.

Isotope	Half-Life	Isotope	Half-Life
Al-26	74,000 years	Fe-55	2.7 years
Co-58	71 days	Cu-64	12.9 hours
Zn-69	56 minutes	Ta-180	8.1 hours
W-181	121 days	Pb-203	52 hours

**7 Radio Frequency Radiation.** Radio frequency radiation (RFR) generating equipment involves the acceleration of electrons across high electric potential and creates x-rays as a byproduct of their operation. The most abundant sources are among radar and high power land-based communication systems. Most modern commercially manufactured systems have effective shielding to limit external radiation dose. Unique high power microwave and ultrawide band systems used in electronic component vulnerability testing also emit x-rays. These devices are fairly unique because few organizations in the AF use them, with some being one-of-a-kind devices that may not have standard safety testing common to commercially manufactured devices. These devices may require more radiation hazard attention and consultation by a health physicist.

(d) **Penetration Range of Photons in Materials.** Photons typically have more significant penetration in materials than do the charged particulate radiations that are emitted by RAM. Photon penetration in materials is generally not treated in the same manner. While charged particle (e.g.,  $\alpha$ - and  $\beta$ -particle) penetration is normally described by the maximum penetration range, photon radiation penetration is generally described in terms of the reduction in exposure for various thicknesses of absorber. Half-value and tenth-value thicknesses are most commonly used. Respectively, these terms refer to the thickness of material required to reduce the exposure rate to one-half and one-tenth of the incident exposure. Table 3-8 provides some example half-value thicknesses for various materials and various photon energies. From the chart, it is obvious that density of the material is the most important factor in absorber effectiveness in photon attenuation. For low energy photons, like those emitted from  $^{241}\text{Am}$  and  $^{109}\text{Cd}$ , and low-energy x-rays, high atomic mass (i.e., high Z) materials, like lead, are more effective attenuators on an equal density thickness basis than low atomic mass materials like water and concrete. For this reason, lead is commonly used as shielding for low-energy photon environments like those from diagnostic x-ray.

For very-low energy diagnostic x-ray environments, like that from mammography, standard building materials, like gypsum may be sufficient shielding for secondary beams (scattered radiation). For higher energy photons, like those from  $^{137}\text{Cs}$  and  $^{60}\text{Co}$ , on an equal density thickness basis, concrete shielding is almost as effective as steel or lead. Due to the lower cost of concrete versus lead and practicality of using concrete in construction, facilities that require shielding for higher energy photons are normally shielded with concrete.



TABLE 3-8. Example Half-Value Thicknesses for Photons (Broad-Beam) in Various Materials.

Radionuclide	Photon Energy (keV)	Half-Value Thickness (cm)			
		Water	Concrete*	Steel	Lead
Am-241	59	4.9	1.4	0.11	0.016 (160 $\mu\text{m}$ )
Cd-109	88	6.4	2.4	0.24	0.034 (340 $\mu\text{m}$ )
Cs-137	662	16	7.4	2.0	0.85
Co-60	1,173/1,332	18	8.5	2.5	1.2
Diagnostic x-ray	100 keV	4.4	1.1	0.09	0.011 (110 $\mu\text{m}$ )
Industrial x-ray	10 MeV	31	14	3.2	1.8

\* density ( $\rho$ ) = 2.2 g/cm<sup>2</sup>

(7) Neutrons. Neutron emissions are not as commonly encountered in AF operations as other forms of radiation previously discussed. The primary source of neutrons is from radioisotope sources. Neutrons are commonly generated by  $\alpha$ -radiation emitting isotopes like <sup>241</sup>Am, <sup>226</sup>Ra, or <sup>239</sup>Pu combined with light elements like beryllium (Be) or lithium (Li). The nuclear absorption reaction, termed an ( $\alpha$ ,n) reaction, emits an  $\alpha$ -particle when a neutron is absorbed by a nucleus. For sources of this type, about 2 and 30 neutrons are produced per million  $\alpha$ -particle emissions in <sup>241</sup>Am and <sup>239</sup>Pu, respectively, and about 400 neutrons per million <sup>226</sup>Ra decays. Neutrons are emitted from these sources across a fairly broad energy range, with mean energy about 4 MeV. The most common in the AF are <sup>241</sup>Am:Be sources that are used in portable moisture density gauges. The next most common source is intrinsic neutron radiation from nuclear weapons that comes from the spontaneous fission of fissionable materials in weapons, primarily from <sup>240</sup>Pu and <sup>238</sup>Pu, and neutrons from nuclear interactions. Examples of a <sup>239</sup>Pu:Be and <sup>235</sup>U fission spectra are provided in Figure 3-4. As discussed earlier, accelerators with energies greater than 10 MeV produce neutrons coincidental to operation. Some of the radioisotope neutron sources used in the AF have significant hazard potential.

Neutrons are characterized by their kinetic energy. Neutrons with energies greater than about 0.1 MeV are termed fast neutrons, neutrons with energies about 0.025 eV are termed thermal neutrons, and neutrons between these energies termed intermediate or slow neutrons. Since neutrons are uncharged particles, they do not interact with materials like  $\alpha$ - and  $\beta$ -particles. For the fast neutrons emitted through nuclear interactions and spontaneous fission, interactions are generally limited to elastic collisions with nuclei, and for this reason neutrons have substantial penetration range in materials. When neutrons are slowed down to near thermal energies, neutron capture mechanisms become important. Hydrogen, <sup>14</sup>N, <sup>10</sup>B, and <sup>113</sup>Cd all are very effective in thermal neutron capture. For fast neutrons, low atomic mass materials like water and carbon are effective attenuators. Concrete is one of the most commonly used shielding material for fast neutrons because it is comprised of low atomic mass material and possesses a significant water fraction.

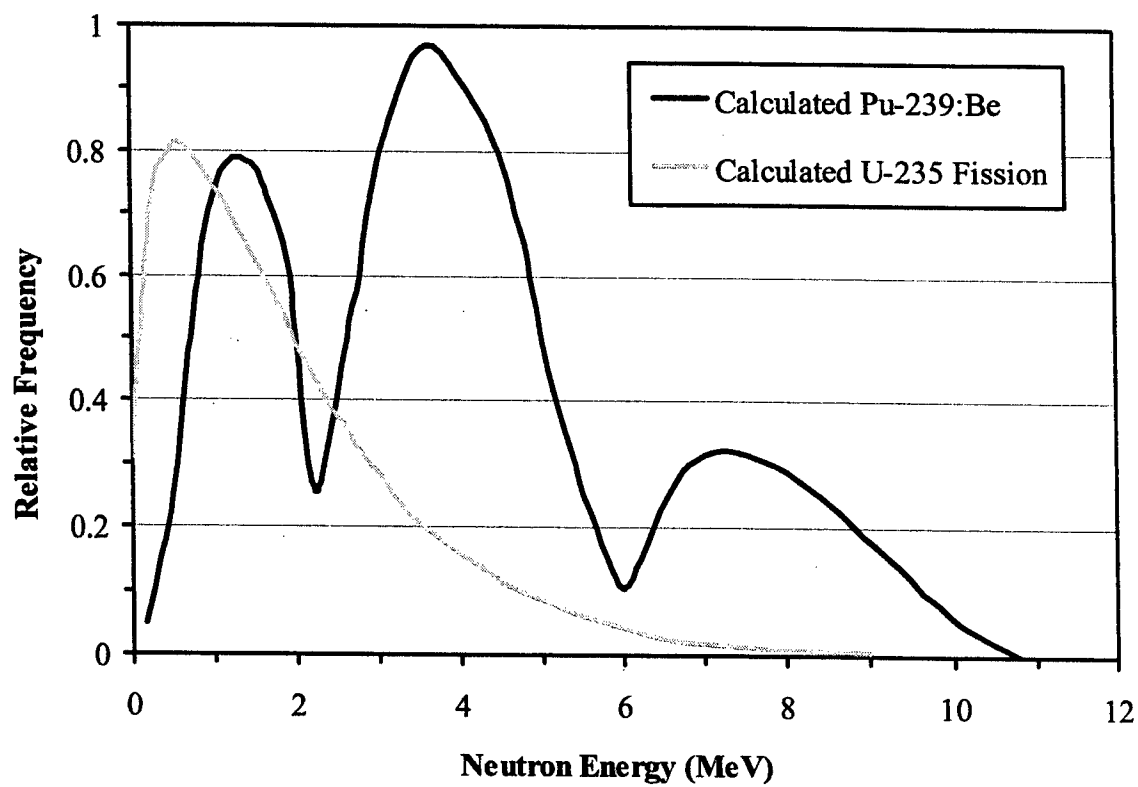


Figure 3-4. Calculated Neutron Spectra.

#### 4. Units of Ionizing Radiation Quantification, Activity, and Half-Life.

a. **Dose.** The absorption of radiation in tissue is the most important factor in determining radiation exposure hazard potential. Absorbed dose is expressed in terms of absorbed energy per unit mass of tissue. The System International (SI) unit is the gray (Gy), which is defined as 1 Joule (J) of absorbed energy per kilogram (kg). The unit is applicable to all type of radiation, independent of whether the dose is received from a source external to the body or from internally-deposited radioisotopes. The historic unit for dose and the one that is still used routinely in the US is the radiation absorbed dose (rad). One gray is equal to 100 rad.

b. **Exposure.** Photon fields in air are quantified in an exposure unit that refers to the amount of energy transferred to a unit mass of air. The unit is quantified by the number of ions (of either sign, positive or negative) produced per kg of air [coulombs/kilogram (C/kg)]. Ionization in air is useful since it is easily measured by instruments. The first exposure unit used was the Roentgen (R) and is equivalent to one statcoulomb of charge (either sign) per  $\text{cm}^3$  of air at  $0^\circ\text{C}$  and 760 mmHg pressure. One R is equivalent to 0.877 rad in air, which is equivalent to 0.97 rad in soft tissue. Since standards are often dose-based, for portable instruments that measure exposure, it is often assumed that **1 R = 1 rad**, since this is a **conservative** assumption and is very close for tissue. For photons with energies above 3 MeV, exposure becomes difficult to measure and the unit is not applicable. For AF operations, this would be applicable to photons produced by high energy accelerators or some industrial x-rays.

c. **Dose Equivalent.** Some radiations, on an equal dose basis, have been demonstrated to be more effective at radiation damage to tissue than other radiations. Generally, the higher the amount of energy transfer per unit length (keV/ $\mu\text{m}$ ), the greater effectiveness of damage. For radiation protection purposes and requirements in meeting regulatory standards, a unit of dose equivalent exists. The historical unit of dose equivalent is the Roentgen equivalent man (rem) and the SI unit is the Sievert (Sv). Both units are related to their respective dose units by a unitless quantity called the quality factor (Q or QF). The NRC-defined Q for licensed materials are listed in

TABLE 4-1. NRC-Defined Quality Factors (Q).

Radiation	Q	Neutron	Energy (MeV)	Q	Neutron	Energy (MeV)	Q
X, $\gamma$ , or $\beta$	1	Thermal	$2.5 \times 10^{-8}$	2	Fast	5	8
$\alpha$ , fission fragments, multiply-charged particles, heavy particles (unknown charge)	20	Slow	$1 \times 10^{-7}$	2		7	7
			$1 \times 10^{-6}$	2		10	6.5
			$1 \times 10^{-5}$	2		14	7.5
			$1 \times 10^{-4}$	2		20	8
			$1 \times 10^{-3}$	2		40	7
			$1 \times 10^{-2}$	2.5		60	5.5
			0.1	7.5		100	4
Neutron (unknown energy)	10	Fast	0.5	11		200	3.5
High-energy Protons	10		1	11		300	3.5
			2.5	9		400	3.5

Table 4-1. BES generally applies external radiation measurements from photons to standards, where Q is one (1). For neutron exposures, the environment must be known or characterized for either thermoluminescent dosimetry (TLD) or by portable neutron monitors. For both measurement types, the quality factor is already applied with TLD results or instrument response in dose equivalent. For internal dosimetry results provided by AFIOH/SDR to installation RSOs and recorded on an individual's lifetime dosimetry history, Q will already be integrated into dose equivalent calculations. Therefore, BES generally will not have to apply these factors as a part of their radiation protection programs.

d. **Units of Activity.** The unit of activity is used to define the number of nuclear transformation (radioactive decay of an atom) events occurring over a period of time. The SI unit for activity is the Becquerel (Bq), where one (1) Bq is equal to one transformation per second (s). The historical unit for activity is the Curie (Ci), which was defined by the number of  $^{226}\text{Ra}$  transformations per second in 1 gram (g) of  $^{226}\text{Ra}$ . One Ci is equal to  $3.7 \times 10^{10}$  Bq.

e. **Half-Life.** Different radionuclides undergo nuclear transformation at different rates. The time for a collection of atoms of one radionuclide to decrease to one-half of its original quantity is called the half-life and illustrated in Figure 4-1. Equation 4-1 is used to calculate the number of atoms (or activity) of a radionuclide based on time and an original quantity:

$$A(t) = A(\text{Original}) * e^{-\left(\frac{0.693 t}{t_{1/2}}\right)},$$

where  $t_{1/2}$  is the half-life,  $A(\text{Original})$  is the quantity and  $A(t)$  is the quantity after an elapsed time,  $t$ .

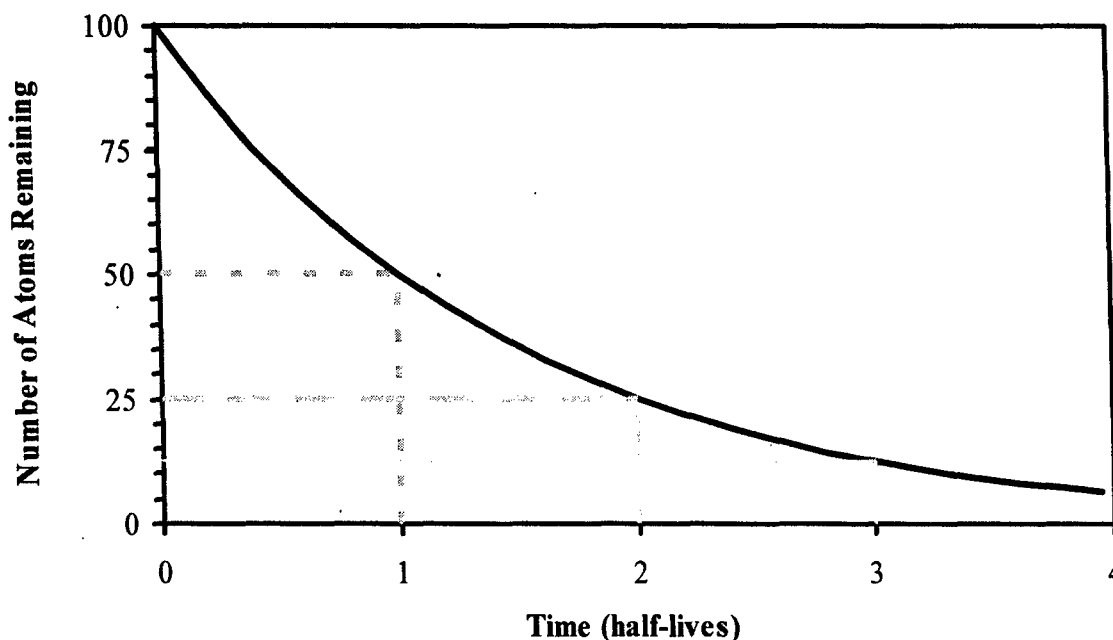


Figure 4-1. Example of Radioactive Half-Life.

## 5. Radiation Protections Standards

a. General. The purpose of the radiation protection standards defined in AFI 40-201 and 48-148 are to ensure that AF workers and members of the general public are not exposed to harmful levels of ionizing radiation. While individual limits are specified for applicable exposure scenarios, it is established throughout most standards for protection from ionizing radiation that all exposures be kept as low as reasonably achievable (ALARA).

b. Exposure Categories for Personnel Exposures. The exposure category of the individual or group being protected must be made for proper application of protection standards. AFI 48-148 recognizes four basic categories for AF operations and personnel.

(1) Occupational. Occupational exposures are those routine exposures incurred as a necessary part of supporting the AF mission and within the responsibility of AF leadership. The types of exposure are vast and encompass many operations from nuclear medicine, research, diagnostic radiology, depleted uranium (DU) munitions handling, nuclear weapons handling and maintenance, and many others. AFI 48-148 also includes many other unique exposures from naturally-occurring sources like radon, and increased cosmic and solar radiation from flight operations.

(2) Medical. Medical exposures are confined to the exposure received by individuals undergoing diagnostic or therapeutic procedures for the diagnosis or treatment of disease to the patient. Excluded from this category are members of the public or family exposed during procedures or volunteer research test subjects.

(3) Exposure to Members of the Public. Exposures to members of the public encompass all routine exposures not considered occupational or medical. In general, most AF operations involving RAM and machine-generated radiations do not provide significant exposure to members of the public. Indoor radon gas and its daughter radiations overall provide the largest source of radiation to members of the public. Exposures incidental to medical diagnostic and therapeutic procedures will provide a lesser degree of exposure.

(4) Accidents/Incidents/Contingencies. Exposures to AF personnel may result from accident or incident scenarios that are not considered routine. These include response activities that may be conducted to save life or property like humanitarian assistance operations or the initial stages of a nuclear weapons accident response. Wartime contingency operations may also involve exposures that are not considered routine like operations in contamination zones created by sabotage or dirty bombs, or nuclear war. Some routine operations like medical diagnostic x-ray, NDI evaluations of components, and loading DU munitions that occur in-garrison, will also be conducted in hostile fire areas. Protective measures and standards applied in-garrison are applicable to deployed locations. Because some facilities in deployed locations are temporary, procedures used in-garrison may be different than those used at deployed locations and may incorporate more administrative controls. Subsequently, these operations may require more BES oversight than those conducted in-garrison.

c. Dose-Equivalent Limits for Individuals. Table 5-1 lists exposure limits promulgated by the NRC. These dose limits are applicable for occupational exposures to adults (18 years and greater)

and minors, the general public, and the embryo/fetus for declared pregnant females. These limits are applicable to NRC-regulated RAM and radiation exposures to other RAM specified in AFI 40-201. Exposures to RAM permitted under the authority of AFI 40-201 to AF organizations are required to follow these limits under a specific condition (usually Condition 13) of their RAM permit authorization. For other routine exposures to ionizing radiation, AFI 48-148 lists these same exposure limits (para. 2.11).

TABLE 5-1. NRC-Promulgated Dose-Equivalent Limits (10 CFR 20).

Application	Occupational (Adults) [Subpart C]	Embryo/Fetus [Subpart C]	Minors (16 – 18 years) [Subpart C]	General Public [Subpart D]
Total Effective Dose Equivalent (TEDE)	50 mSv (5 rem) in a year	N/A	5 mSv (0.5 rem) in a single year	1 mSv (0.1 rem) in a year
Deep Dose- Equivalent & Committed Dose Equivalent	500 mSv (50 rem) to an individual organ or tissue (except lens) in a year	5 mSv (0.5 rem) to embryo/fetus*	50 mSv (5 rem) to an individual organ or tissue (except lens) in a single year	N/A
Lens of the Eye	150 mSv (15 rem) in a year	N/A	15 mSv (1.5 rem) in a year	
Skin	500 mSv (50 rem) in a year		50 mSv (5 rem) in a year	
Extremities	500 mSv (50 rem) in a year		50 mSv (5 rem) in a year	

\* for remainder of declared pregnant females fetal gestation, avoiding substantial monthly variation

For accidents, incidents, and contingency operations, commanders are expected to meet the limits in Table 5-1, where possible. Where not possible, AFI 48-148 specifies alternate dose control guidance (para. 2.12.5, Atch 7-Table A7.1) listed in Table 5-2. The dose guidance also includes recommended protection and surveillance actions, and estimated increased risk of long-term fatal cancers.

While potential radiological accidents or incidents may impact members of the general public, exposure controls will be enforced by civil authorities if the exposures are off base. Civil authorities may request recommendations from installation authorities. Some general public exposures could occur in a RAM accident or incident on-base. For these cases, AFI 48-148 lists recommended intervention levels, based on International Atomic Energy Agency (IAEA) Safety Series 115. Table 5-3 lists the IAEA recommendations. AFMAN 32-4005, para. A3.4.1 (30 Oct 01) provides exposure control guidelines, where for planning purposes total accumulated doses should not exceed 150 centigray (cGy), which is equivalent to 150 rad. However, installation commanders have the authority to adjust the limit, when necessary to ensure critical mission operations.

TABLE 5-2. Operational Dose Guidance for Interventions (NATO Standardization Agreement 2473) from AFI 48-148, Atch 7, Table A7.1

Total Cumulative Doses <sup>1</sup>	Radiation Exposure Status Category	Recommended Protection and Surveillance Actions <sup>2</sup>	Increased Risk of Long-Term Fatal Cancer <sup>5</sup>
0 – 0.5 mSv (0 – 0.05 rem)	0	None	Negligible
0.5 – 5 mGy (0.05 – 0.5 rad)	1A	Record individual doses Initiate periodic environmental monitoring	1:4,000
5 – 50 mGy (0.5 – 5 rad)	1B	Record individual doses Continue monitoring Initiate radiation survey Prioritize tasks Establish dose control measures	1:400
50 – 100 mGy (5 – 10 rad)	1C	Record individual doses Continue monitoring Update radiation survey Continue dose control measures Execute priority tasks only <sup>3</sup>	1:200
100 – 250 mGy (10 – 25 rad)	1D	Record individual doses Continue monitoring Update radiation survey Continue dose control measures Execute critical tasks only <sup>4</sup>	1:80
250 – 750 mGy <sup>6</sup> (25 – 75 rad)	1E	Same as for 1D	1:30

Notes:

1. The use of mSv is preferred in all cases. For low, linear energy transfer (LET) radiations, whole body irradiation (x- and γ-rays): 1cGy = 10 mGy = 1 rad ~ 10 mSv = 1 rem ~ 1 R.
2. All doses should be kept ALARA.
3. Priority task missions to avert danger to persons or to prevent further damage are priority task examples.
4. Missions to save lives are Critical Tasks.
5. In addition to the 1:5 to 1:4 incidence of fatal cancer among members of the general population. Increased risk is given for induction of fatal cancer. Total lifetime risk is assumed to be about 4 – 7 % per 1,000 mGy (100 rad). It must be recognized that higher radiation dose rates produce proportionally more health risks than the same total dose given over longer periods of time.
6. NATA STANAG 2083, *Commander's Guide on Nuclear Radiation Exposure of Groups*, states 1,250 mGy (125 rad) as the commander's upper dose limit.

d. Contamination Limits for Surfaces. Like dose-equivalent limits listed in the previous section, there are numerous sources for recommended limits on surfaces contaminated with RAM. While these limits may appear to be independent of the dose-equivalent limits listed in the previous section, they are fundamentally designed to limit dose-equivalent from external radiation sources and loose RAM that may provide a source of internal exposure. From a practical standpoint, most AF RAM sources are sealed or have limited potential for creating surface contamination. AF

TABLE 5-3. Recommended Generic and Operational Intervention Levels for Protection of the Public (IAEA Safety Series No. 115, 1996) from AFI 48-148, Atch 6, Table A6.2.

Protective Action	Generic Intervention Level (GIL) [Dose avertable by taking protective action]	Operational Intervention Level (OIL) Following a Large Reactor Accident <sup>1</sup>
Sheltering	10 mSv (1 rem) [Not recommended for more than two (2) days]	
Evacuation	50 mSv (5 rem) [Not recommended for more than one (1) week]	1 mSv/h ambient dose rate in plume 1 mSv/h (100 mrem/h) ambient dose rate from deposition
Iodine prophylaxis <sup>2</sup>	100 mGy (10 rad) for adults 50 mGy (5 rad) for children/infants	0.1 mSv/h (10 mrem/h) ambient dose rate in plume
Temporary relocation	30 mSv (3 rem) in the first 30 days 10 mSv (1 rem) in following 30 days	0.2 mSv/h (20 mrem/h) ambient dose rate from deposition
Permanent resettlement	1 Sv (100 rem) in lifetime	

Notes:

1. GILs are difficult to apply in emergency situations since they cannot be promptly measured in the field and do not address the facility or environmental conditions. However, they could be used to develop, as part of the planning, operational intervention levels (OILs). They can be easily measured during an emergency, e.g. ambient dose rate in plume or from deposition, marker radionuclide concentration in deposition or foodstuff and on which the need for protective action can be rapidly ascertained. The values provided were derived for a large nuclear reactor accident.

2. Dosage and periodicity should follow FDA guidance specified in "Guidance for Potassium Iodide as a Thyroid Blocking Agent in Radiation Emergencies," U.S. Department of Health and Human Services.

sources of surface contamination are common to: leaking dials/gauges with <sup>226</sup>Ra, nuclear medicine radionuclide doses, and depleted uranium from 30 mm firing ranges and testing operations, and counter-weight repair.

(1) U.S. Atomic Energy Commission, Regulatory Guide (Reg. Guide) 1.86, "Termination of Operating Licenses for Nuclear Reactors," June 1974. Reg. Guide 1.86 was one of the first regulatory guidance documents on acceptable levels of surface contamination. While the guide was developed for termination of nuclear reactors licenses, the acceptable surface contamination levels listed in Table 1 of Reg. Guide 1.86 have been used for many other applications. While the limits specified in the guide were developed for unrestricted release of material surfaces, these are commonly used for occupational purposes. Also, AFI 48-148, para. 3.4.4.3 (12 Oct 01) recommends their use in the absence of superseding regulatory or advisory guidance. Table 1 of Reg. Guide 1.86 is provided in Table 5-4, with modifications (noted in brackets) as provided in AFI 48-148, Table A4.2. The first column lists radionuclides with the latter three columns listing acceptable levels of contamination. The "Average" and "Maximum" columns refer to total surface contamination, whether it is fixed to the surface or removable. These acceptable surface contamination levels were intended to be assessed through survey by portable instruments. And, the maximum averaging area was set at 100 cm<sup>2</sup> because many portable  $\alpha$ -radiation detection instruments of the time had sensitive detection areas about 100 cm<sup>2</sup>; newer designs of portable  $\alpha$ - and  $\beta$ -detection instruments also use this area in design. The most common error made by many individuals using these acceptable surface contamination levels is in proper determination of the detection efficiency of a particular



instrument/contaminant combination. For  $^{129}\text{I}$  and  $^{90}\text{Sr}$  that are listed in both tables, Reg. Guide 1.86 is 175- and 870-fold, respectively more restrictive than NUREG/CR-5512 using the NRC's Decontamination and Decommissioning (DandD) Software Code.

TABLE 5-4. Reg. Guide 1.86 (1974), Table 1, Acceptable Surface Contamination Levels. (Bracketed portion of notes are extracted from AFI 48-148, Table A4.2 and are not part of original)

Nuclide <sup>a</sup>	disintegrations/minute/100 square-centimeters (dpm/100 cm <sup>2</sup> )		
	Average <sup>b c f</sup>	Maximum <sup>b d f</sup>	Removable <sup>b e</sup>
U-nat, $^{235}\text{U}$ , $^{238}\text{U}$ & associated decay products	5,000 ( $\alpha$ )	15,000 ( $\alpha$ )	1,000 ( $\alpha$ )
Transuranics, $^{226}\text{Ra}$ , $^{228}\text{Ra}$ , $^{230}\text{Th}$ , $^{228}\text{Th}$ , $^{231}\text{Pa}$ , $^{227}\text{Ac}$ , $^{125}\text{I}$ , $^{129}\text{I}$	100	300	20
Th-nat, $^{232}\text{Th}$ , $^{90}\text{Sr}$ , $^{223}\text{Ra}$ , $^{224}\text{Ra}$ , $^{232}\text{U}$ , $^{126}\text{I}$ , $^{131}\text{I}$ , $^{133}\text{I}$	1,000	3,000	200
$\beta$ - $\gamma$ emitters (nuclides with decay modes other than $\alpha$ -emission or SF) except $^{90}\text{Sr}$ and others noted above	5,000 ( $\beta$ - $\gamma$ )	15,000 ( $\beta$ - $\gamma$ )	1,000 ( $\beta$ - $\gamma$ )

Notes:

<sup>a</sup>Where surface contamination by both  $\alpha$ - and  $\beta$ - $\gamma$ -emitting nuclides exists, the limits established for  $\alpha$ - and  $\beta$ - $\gamma$ -emitting nuclides should apply independently. [The values apply to radioactive contamination deposited on, but not incorporated into the interior of, the contaminated item.]

<sup>b</sup>As used in this table, dpm means the rate of emission by radioactive material as determined by correcting the counts per minute observed by an appropriate detector for background, efficiency, and geometric factors associated with the instrumentation.

<sup>c</sup>Measurements of average contamination should not be averaged over more than 1 square meter. For objects of less surface area, the average should be derived for each such object.

<sup>d</sup>The maximum contamination level applies to an area of not more than 100 cm<sup>2</sup>.

<sup>e</sup>The amount of removable radioactive material per 100 cm<sup>2</sup> of surface area should be determined by wiping that area with dry filter or soft absorbent material, applying moderate pressure, and assessing the amount of radioactive material on the wipe with an appropriate instrument of known efficiency. [The use of dry material may not be appropriate for tritium.] When removable contamination on objects of less surface area is determined, the pertinent levels should be reduced proportionally and the entire area should be wiped. [Except for transuranics and  $^{228}\text{Ra}$ ,  $^{227}\text{Ac}$ ,  $^{228}\text{Th}$ ,  $^{230}\text{Th}$ ,  $^{231}\text{Pa}$ , and  $\alpha$ -emitters, it is not necessary to use wiping techniques to measure removable contamination levels if direct scan surveys indicate that the total residual surface contamination (i.e. removable and fixed) are within the limits for removable contamination.]

<sup>f</sup>The average and maximum radiation levels associated with surface contamination resulting from  $\beta$ - $\gamma$ -emitting nuclides should not exceed 0.2 mrad/hr @ 1 cm and 1.0 mrad/hr @ 1 cm, respectively, measured through 7 milligrams per square centimeter (mg/cm<sup>2</sup>) of total absorber.]

## (2) Current NRC Guidance.

(a) The NRC has new guidance on acceptable concentrations of radionuclides on surfaces for license termination, under the NRC's license termination rule [Federal Register, Volume 63, Number 222, Page 64132-64134] and in 10 CFR 20, Subpart E, "Radiological Criteria for

License Termination (LTR).” It is important to note that acceptable surface concentrations developed under this rule meet a total effective dose-equivalent of 25 mrem/yr to an average member of the critical group for unrestricted use. This standard is different than the applications in Table 5-1, even the public exposure application. The source of the difference in the unrestricted LTR limit and that for members of public under 10 CFR 20, Subpart E, is the LTR contemplates that multiple sources of radiation may also contribute dose-equivalent to the average member of the critical group. The LTR assumes a member of the public could have exposure to up to four separate sites and the combined dose-equivalent meets the 100 mrem in a year criterion.

(b) NRC Draft Reg. Guide DG-4006, discusses methods of determining acceptable levels of surface and volumetric contamination for license termination. The Reg. Guide references NUREG-1549 that describes methods for calculating acceptable contamination levels, and NUREG/CR-5512 that provides details on calculation methodology and the use of the NRC’s DandD Software Code. NUREG-1666, Volume 11, Table 11.1 lists some screening levels based on DandD, Version 1 for common radionuclides and listed in Table 5-5. For most radionuclides, specific values calculated under the provisions of NUREG/CR-5512 will be less restrictive than those listed in Reg. Guide 1.86. Guidance on acceptable levels under the LTR should be addressed to AFIOH/SDR and AFMSA/SGPR.

TABLE 5-5. Acceptable License Termination (Unrestricted Release) Screening Values of Common Radionuclides for Building Surface Contamination (Table 11.1, NUREG-1556, Volume 11)\*.

Radionuclide	Screening Level (dpm/100 cm <sup>2</sup> )	Radionuclide	Screening Level (dpm/100 cm <sup>2</sup> )
<sup>3</sup> H	1.2 x 10 <sup>8</sup>	<sup>60</sup> Co	7.1 x 10 <sup>3</sup>
<sup>14</sup> C	3.7 x 10 <sup>6</sup>	<sup>63</sup> Ni	1.8 x 10 <sup>6</sup>
<sup>22</sup> Na	9.5 x 10 <sup>3</sup>	<sup>90</sup> Sr	8.7 x 10 <sup>6</sup>
<sup>35</sup> S	1.3 x 10 <sup>7</sup>	<sup>99</sup> Tc	1.3 x 10 <sup>6</sup>
<sup>36</sup> Cl	5.0 x 10 <sup>5</sup>	<sup>129</sup> I	3.5 x 10 <sup>4</sup>
<sup>54</sup> Mn	3.2 x 10 <sup>4</sup>	<sup>137</sup> Cs	2.8 x 10 <sup>4</sup>
<sup>55</sup> Fe	4.5 x 10 <sup>6</sup>	<sup>192</sup> Ir	7.4 x 10 <sup>4</sup>

\* Screening levels are based on the assumption that the fraction of removable surface contamination is equal to 0.1. For cases where the fraction of removable contamination is undetermined or higher than 0.1, users may assume, for screening purposes, that 100% of surface contamination is removable; and therefore the screening levels should be decreased by a factor of 10. Alternately, users having site-specific data on the fraction of removable contamination (e.g., within the 10 to 100% range) may calculate site-specific screening levels using DandD. The screening values represent surface concentrations of individual radionuclides that would be deemed in compliance with 25 mrem/yr.

(3) Accidents/Incidents/Contingencies. In line with potential exposures discussed in para. 5.b.4, AFI 48-148 references NATO Standardization Agreement 2473, with the same recommendations in Tables 5-6 and 5-7. The recommendations are split into two categories of radionuclides: high-toxicity  $\alpha$ -emitters (all but forms of uranium), and  $\beta$ -emitters and uranium forms (low-toxicity  $\alpha$ -emitters). It is important to note that these are recommendations; installation commanders have the final authority to set appropriate limits, when necessary to ensure critical mission operations.

TABLE 5-6. Military Contamination Limits for 7-day Operation (NATO Standardization Agreement [STANAG] 2473) from AFI 48-148, Atch 7, Table A7.2.

Commander Dose Guidance	Maximum Contamination (Removable) Limits for 7-day Mission Duration (dpm/100 cm <sup>2</sup> )	
	Equipment and Protective Clothing <sup>2</sup>	
	High-Toxicity $\alpha$ -Emitters <sup>1</sup>	$\beta$ - and Low-Toxicity $\alpha$ -Emitters <sup>1</sup>
Category 1A 0.05 – 0.5 rad	30 x 10 <sup>3</sup> (5 Bq/cm <sup>2</sup> )	300 x 10 <sup>3</sup> (50 Bq/cm <sup>2</sup> )
Category 1B 0.5 – 5 rad	300 x 10 <sup>3</sup> (50 Bq/cm <sup>2</sup> )	3,000 x 10 <sup>3</sup> (500 Bq/cm <sup>2</sup> )
Category 1C 5 – 10 rad	600 x 10 <sup>3</sup> (100 Bq/cm <sup>2</sup> )	6,000 x 10 <sup>3</sup> (1,000 Bq/cm <sup>2</sup> )
Category 1D 10 – 25 rad	1,500 x 10 <sup>3</sup> (250 Bq/cm <sup>2</sup> )	15,000 x 10 <sup>3</sup> (2,500 Bq/cm <sup>2</sup> )
Category 1E 25 – 75 rad	4,500 x 10 <sup>3</sup> (750 Bq/cm <sup>2</sup> )	45,000 x 10 <sup>3</sup> (7,500 Bq/cm <sup>2</sup> )

## Notes:

1. If  $\alpha$ -emitting nuclide is undetermined, use high-toxicity column. Low toxicity  $\alpha$ -emitters include uranium forms: natural uranium (<sup>Nat</sup>U), enriched uranium (<sup>En</sup>U), and DU.
2. It is recommended that in Cat 1A, gloves and booties be worn. It is required that in Cat 1B and above, booties, coveralls, gloves, and respiratory protection be worn.

TABLE 5-7. Military Contamination Limits for 3-month Operation (NATO STANAG 2473) from AFI 48-148, Atch 7, Table A7.3.

Commander Dose Guidance	Maximum Contamination (Removable) Limits for 3-month Mission Duration (dpm/100 cm <sup>2</sup> )	
	Equipment and Protective Clothing <sup>2</sup>	
	High-Toxicity $\alpha$ -Emitters <sup>1</sup>	$\beta$ - and Low-Toxicity $\alpha$ -Emitters <sup>1</sup>
Category 1A 0.05 – 0.5 rad	3 x 10 <sup>3</sup> (0.5 Bq/cm <sup>2</sup> )	30 x 10 <sup>3</sup> (5 Bq/cm <sup>2</sup> )
Category 1B 0.5 – 5 rad	30 x 10 <sup>3</sup> (5 Bq/cm <sup>2</sup> )	300 x 10 <sup>3</sup> (50 Bq/cm <sup>2</sup> )
Category 1C 5 – 10 rad	60 x 10 <sup>3</sup> (10 Bq/cm <sup>2</sup> )	600 x 10 <sup>3</sup> (100 Bq/cm <sup>2</sup> )
Category 1D 10 – 25 rad	150 x 10 <sup>3</sup> (25 Bq/cm <sup>2</sup> )	1,500 x 10 <sup>3</sup> (250 Bq/cm <sup>2</sup> )
Category 1E 25 – 75 rad	450 x 10 <sup>3</sup> (75 Bq/cm <sup>2</sup> )	4,500 x 10 <sup>3</sup> (750 Bq/cm <sup>2</sup> )

## Notes:

1. If  $\alpha$ -emitting nuclide is undetermined, use high-toxicity column. Low toxicity  $\alpha$ -emitters include uranium forms: natural uranium (<sup>Nat</sup>U), enriched uranium (<sup>En</sup>U), and DU.
2. It is recommended that in Cat 1A, gloves and booties be worn. It is required that in Cat 1B and above, booties, coveralls, gloves, and respiratory protection be worn.

e. Department of Transportation (DOT) Standards for Transport of Radioactive Materials.

(1) General. There are two primary radiation standards that are commonly applicable to many day-to-day shipments of radioactive materials from AF bases: radiation level limitations specified in 49 CFR 173.441 and contamination control specified in Part 173.443. Generally, packages will be transported by ground or air travel. For ground transport, DOT regulations are applicable to public roads. For RAM transport on AF installations, DOT regulations are not applicable if access is restricted from the public. This is true for most AF installations. For air transport, DOT regulations are applicable for commercial air transport but not military air [49 CFR 175.5(a), "... This part does not apply to: (1) Aircraft owned or operated by a government when not engaged in carrying persons or property for commercial purposes."] For transport overseas, adherence to host country transport regulations is required. International Atomic Energy Agency (IAEA) regulation IAEA TS-R-1 is accepted by many countries. The International Air Transport Association (IATA) Dangerous Goods Regulation is reflected in Chapter 10 of IAEA TS-R-1 for air transport and has applicability to overseas AF shipments. The transportation management office (TMO) is responsible for most RAM transport issues, and follows AFI 24-202 and AFJI 24-210.

(2) Radiation Levels. 49 CFR 173.441 specifies radiation limits for packages under routine transport modes and for exclusive use transport (sole use, shipment is under control of the cosignee for the duration of the transport). 49 CFR 172.403 specifies RAM package labels for various external radiation dose-equivalent levels. Unique radiation limits are also specified for packages that are excepted from DOT specification packaging, marking, and labeling as specified in 49 CFR 173.421 - .426. Table 5-8 provides a listing of appropriate dose-equivalent levels from the three references. While specified limits are in dose-equivalent values, most AF shipments have  $\gamma$ - and x-radiations emissions only, and measurements of exposure in Roentgen units are approximately equal to dose-equivalent in Rem. Notable exceptions are portable moisture density gauges that contain neutron sources and a few organizations that possess neutron sources not contained in a device. Outside of several AFMC installations, neutron radiation detectors are not common.

(3) Contamination Levels. Table 11 in 49 CFR 173.443 lists contamination limits for all packages offered for transport. A modified version of this table is in Table 5-9. It is important to note that the definition of low-toxicity  $\alpha$ -emitters is different than that of NATO STANAG 2473 and other applications. The requirement for meeting DOT removable contamination limits on the external surface of packages is often confused with NRC leak testing requirements. All packages containing RAM must meet the DOT external contamination limits prior to transport by modes under DOT regulations. This is in addition to the NRC requirement of having a current leak test (on those sealed sources that require it) prior to packaging and transfer of a source.

(4) Package Receipt Monitoring Requirements. While paragraphs (2) and (3) above list requirements for RAM shipments, packages with NRC-licensed or AF-permitted RAM labeled with "Radioactive White I, Yellow II or III" require radiation and contamination assessments within three (3) hours of receipt during a normal work day, or within three (3) hours of the next working day. Exceptions to the external contamination assessment exist for gaseous or special form, and to radiation measurements, if less than Type A quantities. If levels are in excess of the DOT limits, the receiver is required to notify the carrier and the NRC. In the AF, NRC notification is made through the AF Radioisotope Committee (RIC) Secretariat (AFMSA/SGPR).

TABLE 5-8. DOT Radiation Limits and Label Categories  
(49 CFR 172.403, 173.441, and 173.421 - .426).

Dose-Equivalent Rate (mrem/hr)			Class 7 Quantity or Label Category
Transport Index (TI) @ 1-meter from Package Surface (round to nearest tenth)	Maximum @ Any Point on External Surface of Package	Maximum @ 10 cm from any point on External Surface of Unpackaged Instrument or Article	
NA	0.5	NA	Excepted Package- Limited Quantity & Manufactured Articles
	0.5	10	Excepted Package- Instrument or Article
	2	10	Excepted Package- Instrument or Article (Exclusive Use)
TI $\leq$ 0.05	$\leq$ 0.5	NA	WHITE-I
0.05 < TI $\leq$ 1	> 0.5, but $\leq$ 50		YELLOW-II
1 < TI < 10	> 50, but $\leq$ 200		YELLOW-III
> 10	> 200, but $\leq$ 1,000		YELLOW-III (Exclusive Use)

TABLE 5-9. DOT Non-Fixed (Removable) Contamination Limits for  
External Surfaces of Packages (Modified from Table 11, 49 CFR 173.443).

Contaminant	Maximum Permissible Limits <sup>1</sup>			
	per cm <sup>2</sup>		per 300 cm <sup>2</sup>	
	Becquerel	dpm	Becquerel	dpm
$\beta$ - and $\gamma$ - emitters, and low-toxicity $\alpha$ -emitters <sup>2</sup>	0.4	22	120	6,600
All other $\alpha$ -emitting radionuclides	0.04	2.2	12	660

Notes:

1. 49 CFR 173.442(a)(1) specifies that an area of 300 cm<sup>2</sup> on the external surface of a package shall be wiped and sufficient measurements must be taken in the most appropriate locations to yield a representative assessment of non-fixed contamination levels.
2. Low-toxicity  $\alpha$ -emitters are: natural uranium, depleted uranium, and natural thorium; and ores, concentrates, or tailings containing <sup>235</sup>U, <sup>238</sup>U, <sup>232</sup>Th, <sup>228</sup>Th, <sup>230</sup>Th, and those with half-life less than 10 days.

(5) Activity Limits for Limited Quantities, Instruments, and Articles. Table 7 of 49 CFR provides limits for limited quantities, and instruments and articles under Parts 173.421 to .426. A modified version of this table is in Table 5-10. DOT A<sub>1</sub> and A<sub>2</sub> values for common AF nuclides are listed in Table 5-11. The differences among radionuclides for A<sub>1</sub> and A<sub>2</sub> values is based on relative radiotoxicity, with lower radiotoxic radionuclides having higher A<sub>1</sub> and A<sub>2</sub> values than more

radiotoxic ones.  $A_1$  values for special forms are always equal to or higher than  $A_2$  values for normal form. For elements like  $^{241}\text{Am}$ , most  $\alpha$ -emitting radionuclides, and some  $\beta$ -emitting radionuclides, there is a significant difference between the  $A_1$  and  $A_2$  value. Therefore, for these there is significant advantage in allowable activity if a source qualifies as special form. Manufacturers typically certify sources as "special form" and provide certificates to users. Re-certification is normally required every three (3) years. Special form RAM is a single solid piece or a sealed capsule that can only be opened by destroying the capsule, has at least one dimension not less than five (5) mm, and has met testing requirements of 49 CFR 173.469. If a source's status as a special form is not known, normal limits should be applied.

TABLE 5-10. DOT Activity Limits for Limited Quantities, Instruments, and Articles  
(Modified from Table 7, 49 CFR 173.425, 1 Oct 04).

Nature of Contents		Instruments and Articles <sup>1</sup>		Limited Quantity Package Limits <sup>1</sup>
State	Form	Limits for each instrument or article	Package limits	
Solid	Special	0.01 $A_1$	$A_1$	0.001 $A_1$
	Normal	0.01 $A_2$	$A_2$	0.001 $A_2$
Tritiated Water	< 0.1 Ci/L	NA		1,000 Ci (37 MBq)
	0.1 – 1.0 Ci/L			100 Ci (3.7 MBq)
	> 1.0 Ci/L			1 Ci (37 kBq)
Liquids	Other than tritium	0.001 $A_2$	0.1 $A_2$	0.0001 $A_2$
Gases	Tritium <sup>2</sup>	0.02 $A_2$	0.2 $A_2$	0.02 $A_2$
	Special	0.001 $A_1$	0.01 $A_1$	0.001 $A_1$
	Normal	0.001 $A_2$	0.01 $A_2$	0.001 $A_2$

Notes:

1. The rules in Part 173.433(d) apply to mixtures, which is application of the sum of fractions rule.
2. These values apply to tritium in activated luminous paint and tritium adsorbed on solid carriers.

f. Classifying Areas in the Proximity of Radiation Sources.

(1) General. AFI 48-148, Para. 3.2.2 describes the criteria for classification of areas in the proximity of radiation sources. The purpose of the classification is to ensure exposures are within applicable standards and ALARA, and aid in determining necessary surveillance, postings, and other requirements. In general, the AF does not recognize a difference in the source of radiation, whether machine-generated, NRC-licensed RAM, naturally-occurring RAM, or accelerator-produced RAM; criteria are based on 10 CFR 20.

(2) Unrestricted Areas. Unrestricted areas are those that are not controlled and meet the dose limits for individual members of the public, **100 mrem in a year**, excluding sources of radiation from background, medically administered doses, doses from other individuals released under provisions of 10 CFR 35.75 (i.e., patients possessing body burdens of therapeutic radionuclides like  $^{131}\text{I}$ ), and sanitary sewer releases. Further, these areas must also meet a dose-equivalent limit of **2 mrem** (at 30 cm from the source) **in any one (1) hour** from external radiation sources (i.e., external to the body).

TABLE 5-11. DOT A<sub>1</sub> and A<sub>2</sub> Values of Radionuclides used in AF\* (49 CFR 173.435, 1 Oct 04).

Radionuclide	Activity (Ci)		Radionuclide	Activity (Ci)	
	A <sub>1</sub> (special)	A <sub>2</sub> (normal)		A <sub>1</sub> (special)	A <sub>2</sub> (normal)
H-3	1100	1100	Xe-133 (gas)	540	270
C-14	1100	81	Cs-137	54	16
F-18	27	16	Pm-147	1100	54
Na-24	5.4	5.4	Re-187	Unlimited	Unlimited
P-32	14	14	Ir-192	27	16
Fe-55	1100	1100	Tl-201	270	110
Co-57	270	270	Po-210	1100	0.54
Co-60	11	11	Ra-226	5.4	0.081
Ni-63	1100	810	Th-230	270	0.027
Ga-67	190	81	Th-232	Unlimited	Unlimited
Kr-85 (gas)	270	270	U-234	1100	0.16 **
Sr-90	8.1	8.1	U-235	Unlimited	Unlimited
Y-90	8.1	8.1	U-238	Unlimited	Unlimited
Mo-99	27	16	<sup>En</sup> U (≤ 20 %)	Unlimited	Unlimited
Tc-99m	270	110	<sup>En</sup> U (> 20 %)	1100	0.16 **
Pd-103	1100	1100	<sup>Nat</sup> U	Unlimited	Unlimited
Cd-109	810	54	DU	Unlimited	Unlimited
In-111	81	81	Pu-238	270	0.027
I-123	160	81	Pu-239	270	0.027
I-125	540	81	Pu-240	270	0.027
I-131	81	19	Am-241	270	0.027

\* Complete list in 49 CFR 173.435 & general values (Table 10) for unknowns. For TBq, divide by 27.

\*\* Slow lung absorption – UO<sub>2</sub>, U<sub>3</sub>O<sub>8</sub>, & metals. See 49 CFR 173.435 for other forms. <sup>En</sup>U = U enriched in <sup>235</sup>U.

(3) Restricted Areas. These are the areas where specific protective measures exist or could be required for controlling routine radiation exposure, preventing access to radiation sources, or preventing the spread of contamination during normal work practices. Access to these areas can take many forms, dependent on the characteristics of the area and individual involved. In general, employees working in a particular area are granted access based on the job requirements and knowledge/training in hazards/controls in the workplace. Employees, from other work areas, that periodically access these areas, generally do so under the supervision of individuals responsible for the restricted area. Visitors and patients (for medical-use areas) shall be escorted. Provisions should be made by an RSO, or other responsible individual, for granting unescorted access by non-employees. Visitors to restricted areas should be issued temporary radiation monitoring (i.e., pocket ionization, electronic personnel dosimeter, etc.) and have the monitoring results recorded, if it is deemed necessary in ensuring that limits to members of the general public are met.

(a) Radiation Areas. Radiation areas are those with accessible radiation levels that could result in an individual receiving a dose-equivalent in excess of 5 mrem in any one (1) hour at 30 cm from the source or from any surface that the radiation penetrates. These restricted areas must have "Caution, Radiation Area" postings. In addition, if licensable amounts of RAM are creating the

exposure and quantities exceed ten times Appendix C, Part 20 limits, "Caution, Radioactive Material" postings must be made. Posting exceptions exist for medical x-ray rooms and others discussed below.

(b) High Radiation Areas. High radiation areas are those with accessible radiation levels that could result in an individual receiving a dose-equivalent in excess of 100 mrem in any one (1) hour at 30 cm from the source or from any source that the radiation penetrates. These restricted areas must have "Caution, High Radiation Area" postings. In addition, if licensable amounts of RAM are creating the exposure, "Caution, Radioactive Material" postings must be made. Posting exceptions exist for medical x-ray rooms and others discussed below. 10 CFR 20.1601 specifies controls for these areas and that will be described later in this report.

(c) Very High Radiation Areas. Very high radiation areas are those with accessible radiation levels that could result in an individual receiving an absorbed dose in excess of 500 rad in any one (1) hour at one (1) meter from the source. These restricted areas must have "Grave Danger, Very High Radiation Area" postings. In addition, if RAM is creating the exposure, "Danger, Radioactive Material" postings must be made. Posting exceptions exist for medical therapy rooms and others discussed below. 10 CFR 20.1601-1602 specifies controls for these areas and that will be described later in this report, but are normally overseen by a medical physicist.

(d) Airborne Radioactivity Area. These are areas that have derived air concentrations (DACs) of licensed radioactive materials above NRC occupational limits or 12 DAC-hours based on the exposure an individual would receive without respiratory protection during the hours present in a week. These restricted areas must have "Caution, Airborne Radioactivity Area" postings. Posting exceptions exist as discussed below. One DAC is equivalent to the occupational limit for airborne concentrations of RAM based on a 2000 hour work year.

(4) Posting Exceptions for Restricted Areas. 10 CFR 20.1903 provides posting exceptions for licensed materials.

(a) Caution sign postings are not required for periods of eight (8) hours or less if RAM is constantly supervised to control exposure within applicable limits and the areas are under administrative control of the responsible organization.

(b) Caution sign postings are not required in areas or rooms of medical facilities where the exposure is the result of a patient released under provisions of 10 CFR 35.75.

(c) Caution signs postings are not required in areas/rooms that require posting solely due to radiation emitted from a sealed source(s), provided the dose-equivalent at 30 cm from the source(s) or housing is less than 5 mrem/hr. This exemption is for many AF RAM storage and use areas that have sealed sources, like chemical agent detectors, lead-based paint analyzers, etc. Though this exemption exists, the AF recommends as a good practice to post these areas.

(d) Caution signs are not required in rooms of medical facilities used for teletherapy if the room is controlled according to procedures in 10 CFR 35.615 and radiation exposures are contained within applicable limits.



(5) Controls for High and Very High Radiation Restricted Areas (10 CFR 20.1601).

(a) Each entrance or access point to these areas must have one or more of the following:

1 control device (i.e., an interlock) that upon entry limits dose-equivalent that an individual might receive to 100 mrem in any one (1) hour at 30 cm from the source or any surface that the radiation penetrates; or

2 control device that energizes a conspicuous visible or audible alarm to the individual entering and supervisor of the operation that an entry has occurred; or

3 locked entries, except when access is required, with positive control over each entry.

(b) In place of the controls in a) above, direct or electronic surveillance that is capable of preventing unauthorized access must be used.

(c) Controls must not prevent individuals from leaving a high radiation area.

(d) Controls are not required for entrance or access points solely because of the presence of RAM prepared for transport and packaged in accordance with DOT requirements if: they do not remain for more than three (3) days and if the dose-equivalent rate at one (1) meter from the surface of the package dose not exceed 10 mrem/hr.

(e) Access controls to rooms are not required solely because a patient contains radioactive material if personnel are in attendance to contain exposures within applicable limits and an organization's ALARA program.

(6) Controls for Very High Radiation Restricted Areas (10 CFR 20.1602). For these areas, additional measures must be in place that upon entry limits dose-equivalent an individual might receive to 500 rad in one hour at 1 m from the source or any surface that the radiation penetrates.

g. Licensing of Radioactive Material and AF-Permitting System.

(1) General.

(a) The Atomic Energy Act (AEA) of 1954 and the Energy Reorganization Act of 1974 give the NRC authority to regulate Byproduct Material, Source Material, and Special Nuclear Material (SNM), except material listed in Section 91. Section 91 contain three exemptions: 91a, exempts the Department of Energy (DOE) for the use of material in research, development, and construction of materials for defense; 91b, exempts the DoD for defense-related RAM developed and constructed by DOE; and 91c, provides authority for the DOE to transfer the same materials to foreign entities. The Section 91b exemption relates primarily to RAM in nuclear weapons and associated equipment, and military-unique nuclear reactors. These materials are self-regulated by the DoD, and within the AF are subject to AFI 91-108, "Air Force Nuclear Weapons Intrinsic Radiation Safety Program," and AFI 91-109, "Air Force Nuclear Reactor Program."

(b) For RAM under the authority of the NRC, the AF possesses a Master Materials License from the NRC that provides broad authority and responsibility for permitting RAM use in the AF. AFI 40-201 provides comprehensive instruction on how this is accomplished for NRC-licensed materials, and accelerator-produced and naturally-occurring RAM, that while not under NRC jurisdiction, can be subject to AF permitting.

(2) NRC Licensing/AF Permitting. Licensing of RAM under the provisions of 10 CFR has multiple categories of licensing provisions dependent on the type of material and license type: specific or general. Table 5-12 contains a summary of common AF RAM sources and activities that are licensed under NRC (and subsequently may require an AF permit or require registration as a generally-licensed device) and those that are permitted by the AF under AFI 40-201. The most important criterion for licensing/permitting is the RAM category and the use. The NRC has three categories, as defined below.

(a) Byproduct Material. Any RAM [except special nuclear material (SNM), see below] yielded in or made radioactive by exposure to the radiation incident to the process of producing or utilizing SNM. Generally, this encompasses RAM produced by nuclear reactor operations.

(b) Source Material. Uranium or thorium, or any combination thereof, in any physical or chemical form or ores which contain by weight one-twentieth of one percent (0.05%) or more of uranium, thorium, or any combination thereof.

(c) Special Nuclear Material (SNM). Plutonium,  $^{233}\text{U}$ , uranium enriched in  $^{233}\text{U}$  or  $^{235}\text{U}$ .

(d) Whether an NRC-licensed material requires a specific AF permit or meets the general licensing provisions of NRC is dependent on the radioisotope, device that it being used, total activity, and intended use. The most common generally-licensed devices used in the AF are Ionscans, the APD-2000, tritium exit signs, ice detectors, static eliminators, and in-flight blade inspection systems (IBIS), as shown in Table 5-12. For IBIS systems, the AF has decided to specifically license these sources. From Table 5-12, a number of accelerator-produced and naturally-occurring RAM require specific AF permits. Most commonly, these involve some nuclear medicine radioisotopes,  $^{226}\text{Ra}$ , or  $^{109}\text{Cd}$  as used in lead-based paint analyzers.

(3) Isotopes with Dual Production. Some RAM sources may have production that falls under the NRC byproduct definition or that of an accelerator. Those common to use in the AF are:  $^{109}\text{Cd}$ ,  $^3\text{H}$ , and  $^{60}\text{Co}$ . In general,  $^{109}\text{Cd}$  used in NITON Corp. lead-based paint analyzers is accelerator-produced, while  $^3\text{H}$  and  $^{60}\text{Co}$  used in the AF are byproduct RAM under NRC.

(4) Generally-Licensed Devices. Many AF organizations that possess devices that are generally-licensed by the NRC believe that the RAM is considerably easier to handle because an AF permit is not required. To the contrary, most of the requirements for specifically-permitted RAM are the same as that of NRC generally-licensed RAM. Table 5-13 provides a summary of key requirements for AF permitted and generally-licensed RAM. From the table, while specific permittees must apply and receive approval permit issuance, generally-licensed RAM must be registered with the AF RIC, and a subset with the NRC. Specifically-permitted and some categories of generally-licensed RAM must meet requirements in 10 CFR Parts 19, 20, and 21.

TABLE 5-12. Permitting Authority for Common AF RAM Sources/Activities

Authority	RAM Category	RAM	Licensed/Permitted AF Activity
10 CFR 30	Byproduct	Ni-63	CAM, ICAM, ACADA (M-22)
		Am-241	Chemical Agent Alarms, LANTIRN/SNIPER Pods, Static Eliminators, Check Sources
		Cs-137, Am-241	Portable Moisture Density Gauges (i.e., Troxler Gauges)
		Cs-137, Co-60	Calibration, Irradiator
		Fe-55, Am-241	Lead-Based Paint Analyzers (i.e., NITON gauges)
		Sr-90	Radioisotope Thermal Generators
		C-14	Astroinertial Navigation Devices
10 CFR 31	Generally Licensed Byproduct	Ni-63	APD-2000, Ionscans, Gas Chromatographs
		H-3	Exit Signs
		Po-210	Static Eliminators
		Sr-90	Ice Detectors, In-flight Blade Inspection System (IBIS)**
10 CFR 35	Medical Use of Byproduct	Mo-99, Tc-99m, Pd-103, I-125, I-131, Xe-133, Tl-201	Nuclear Medicine
10 CFR 40	Source	<sup>Nat</sup> Th	Training Sites, MagThor Alloy Recycling
		DU	Distribution, Storage, Testing, Research, Development, and Remediation of Spent 30 mm Rounds
		DU, <sup>Nat</sup> U	Biological Research
		DU, <sup>Nat</sup> U	Recycling
		DU	Counterweight Repair
10 CFR 70	SNM	Pu-239, U-235	Calibration & Neutron (w/ Be)
	Generally Licensed SNM	Pu-239 (< 5 µCi)	Calibration
AFI 40-201	Accelerator-Produced	F-18, Ga-67, In-111, I-123, Co-57	Nuclear Medicine
	Naturally-Occurring	Ra-226	Luminous Products, Neutron Sources (w/ Be)
	Accelerator-Produced	Cd-109*	Environmental Remediation Lead-Based Paint Analyzers (i.e., NITON gauges)

\* Can also be byproduct material under NRC regulations

\*\* IBIS are distributed as 10 CFR 31.5 gauging devices, but the AF **specifically** permits these devices.

TABLE 5-13. Key Requirements for Organizations Possessing NRC Generally-Licensed (GL) and AF Specifically-Permitted RAM.

Regulatory Requirement (10 CFR)	AF Specifically- Permitted RAM	Generally-Licensed (GL) Materials			
		Part 31.3 Ion Generating Tubes & Static Eliminators ( $^3\text{H}$ , $^{210}\text{Po}$ )	Part 31.5 Measuring, Gauging, Controlling Devices, Exit Signs	Part 31.7 Luminous Safety Devices in Aircraft ( $^{210}\text{Po}$ , $^3\text{H}$ )	Part 31.10 Ice Detectors ( $^{90}\text{Sr}$ )
Permit Application & Approval	X	---	---	---	---
Device Registration with NRC & AF RIC	---	---	$^{137}\text{Cs} \geq 10 \text{ mCi}$ $^{90}\text{Sr} \geq 0.1 \text{ mCi}$ $^{60}\text{Co} \geq 1.0 \text{ mCi}$ transur. $\geq 1 \text{ mCi}$	---	X
Device Registration with AF RIC	---	---	X	---	---
Part 19 – Notices, Instructions and Reports to Workers	X	X	---	---	X
Part 20 – Standards for Protection Against Radiation	X	X	only 20.2201 - .2202	only 20.2201 - .2202	only 20.2001 & 20.2201 - .2202
Part 21 – Reporting of Defects and Noncompliance	X	X	---	---	X
Leak Testing	Sealed Sources per SSDR*	Sealed Sources per SSDR* ( $^{210}\text{Po}$ static eliminators – 13 months)	$\beta/\gamma$ -emitters > 100 $\mu\text{Ci}$	---	---
			$\alpha$ -emitters > 10 $\mu\text{Ci}$		
			$^3\text{H}/^{85}\text{Kr}$ exempt		
Periodic Source Inventories	X	---	---	---	---
Source Labelling	X	X	X	X	X
DOT Shipping Requirements	X	X	X	X	X
RAM Container Labelling	X	X	Maintain GL Label		X
Transfers		Transfers Only to Specific Licensees/Permittees			
Disposal		According to NRC/AFI 40-201			

\*SSDR – Sealed Source and Device Registry database maintained by NRC.

Most important are requirements of Part 20, which are applicable in full to Part 31.3 devices, and in-part to Part 31.5, 7, and 10 devices. Part 20.2201 lists requirements for reporting thefts and loss of RAM, Part 20.2202 lists reporting requirements for incident reporting, and Part 20.2001 covers waste disposal requirements. Just as important are the similar restrictions on transfers of RAM, DOT shipping requirements, and disposal requirements. Like specifically-permitted RAM, generally-licensed materials **cannot** be transferred to other organizations in the AF or outside the AF, unless the receiving organization possesses a specific AF or Navy permit, or an NRC or agreement state specific license that allows possession of that RAM. For example, a security force organization at one base **cannot** transfer an ADP-2000 to an organization at another installation, unless the receiving organization possesses a **specific permit** that authorizes the possession. Further, because these devices are not tied to a specific permit, some organization may attempt to dispose of the equipment through the Defense Reutilization and Marketing Office (DRMO) or to a municipal landfill. Disposals through DRMO of any RAM are not permitted. Another implication of this restriction may arise for tritium exit signs (10 CFR 31.3), when buildings are demolished under contract. The entity conducting the demolition cannot take possession of the signs unless they are licensed (or permitted) as discussed above.

While not listed in Table 5-13, two other categories other generally-licensed RAM may be used in AF operations. 10 CFR 31.11 is applicable to byproduct RAM uses in certain in vitro clinical or laboratory testing with  $^3\text{H}$ ,  $^{14}\text{C}$ ,  $^{59}\text{Fe}$ ,  $^{75}\text{Se}$ ,  $^{125}\text{I}$ , and  $^{131}\text{I}$ . 10 CFR 40.22 is applicable to small quantities of source material, where individual transfers are less than 15 pounds, and less than 150 pounds is received in a calendar year.

(5) Exempt Quantities. Some quantities of RAM are exempt from the provisions a specific and general license under NRC.

(a) Byproduct Material. Schedule A, 10 CFR 30.70 contains exempt concentrations of byproduct material, while Schedule B, 10 CFR 30.71, contains exempt quantities of byproduct material. Exempt quantities of RAM common to AF operations are listed in Table 5-14. Table 5-15 contains a listing, regulatory reference, and limits for other exempt byproduct items. These devices are used in the AF and are incorporated in many types of equipment. It is important to note that the NRC exemption for these items is based on their intended use. Alterations or modifications for the purposes of volume reduction, recycling, waste consolidation, etc. requires a specific AF permit. Additionally, once material is licensed it is always licensed. RAM cannot be decayed to exempt quantity status.

(b) Source Material. Source material has a number of exemptions from 10 CFR 40 requirements. Table 5-16 contains a list of exempt source material common to AF. Like NRC exemptions for byproduct material, these items are exempt from a specific permit if used for the intended purpose. While exempt from AF permitting, other NRC requirements must be kept. Operations involving repair of damaged DU counterweights and altering MagThor alloyed aircraft parts require specific AF permits.

(c) Other Materials. Naturally-occurring and accelerator-produced RAM are regulated in the AF under AFI 40-201. Attachment 2 of the AFI lists exempt quantities for these two categories of RAM. For isotopes not on this list, contact the AF RIC for directions.

TABLE 5-14. NRC Exempt Quantities of Byproduct Material  
Common to AF Operations (10 CFR 30.71, Schedule B).

Radioisotope	Quantity ( $\mu\text{Ci}$ )	Radioisotope	Quantity ( $\mu\text{Ci}$ )
C-14	100	Kr-85	100
Na-24	10	Sr-90/Y-90	0.1
P-32	10	Cd-109	10
Cl-36	10	Cs-137	10
Fe-55	100	Pm-147	10
Co-60	1	Po-210	0.1
Ni-63	10		

TABLE 5-15. NRC Exempt Byproduct Material Items with Regulatory Reference and Limits.

Item	Radioisotope	Limit	Regulatory Reference
Electron tubes:  (include spark gap tubes, power tubes, gas tubes including glow lamps receiving tubes, microwave receiver protector tubes*, indicator tubes, pickup tubes, radiation detection tubes, and other completely sealed tube that is designed to control electrical currents)	H-3*	150 mCi	10 CFR 30.15(a)(8)
	H-3	10 mCi	
	Ni-63	5 $\mu\text{Ci}$	
	K-85	30 $\mu\text{Ci}$	
	Cs-137	5 $\mu\text{Ci}$	
	Pm-147	30 $\mu\text{Ci}$	
	Co-60	1 $\mu\text{Ci}$	
Spark gap irradiators (ignition)	Co-60	1 $\mu\text{Ci}$	10 CFR 30.15(a)(10)
Gas & aerosol detectors (e.g. smoke detectors)	Am-241	1 $\mu\text{Ci}$	10 CFR 30.20
Timepieces or hands or dials	H-3	25 mCi/timepiece	10 CFR 30.15(a)(1)
		5 mCi/hand	
		15 mCi/dial	
	Pm-147	100 $\mu\text{Ci}$ /watch	
		200 $\mu\text{Ci}$ /other $^{147}\text{Pm}$ timepiece	
		20 $\mu\text{Ci}$ /watch hand	
		40 $\mu\text{Ci}$ /other $^{147}\text{Pm}$ timepiece hand	
		60 $\mu\text{Ci}$ /watch dial	
		120 $\mu\text{Ci}$ /other $^{147}\text{Pm}$ timepiece dial	
Ionizing radiation measuring instruments containing for purpose of internal calibration or standardization	Each Source	< Schedule B	10 CFR 30.15(a)(9)
	Instrument	< 10 Exempt Quantities	
	Am-241	0.05 $\mu\text{Ci}$	

TABLE 5-16. NRC Exempt Source Material with Regulatory Reference.

Material	Radioisotope	Reference
Lantern mantles, vacuum tubes, welding rods	Thorium	10 CFR 40.13(b)(1)
MagThor alloy in finished parts/products	Thorium (< 4% by weight)	10 CFR 40.13(b)(4)
Counterweights	<sup>Nat</sup> U and Depleted Uranium	10 CFR 40.13(b)(5)*
Shielding as part of shipping container	<sup>Nat</sup> U and Depleted Uranium	10 CFR 40.13(b)(6)
Thoriated optical lens/coatings (except: contact lenses, binoculars, spectacles)	Thorium (≤ 30% by weight)	10 CFR 40.13(b)(7)

\* NRC deems that long-term holding (> 24 months) of a counterweight (i.e., not installed on an aircraft) is not covered under the exemption (NRC 2005). As well, long-term holding on static aircraft displays are not covered by the exemption, and require a specific AF permit.

(d) Other AF Mandates. In addition to specific AF permits and in lieu of a permit, the AF has other documents that provide specific requirements. AFI 84-103 has requirements for RAM contained in static display aircraft (e.g. dials, gauges, oxygen indicators, counterweights, thoriated-glass). MagThor and DU counterweights have requirements listed in individual system technical order (TO) documents. AFI 23-504 lists requirements for handling radioactive commodities in the DoD supply system.

(6) Machine-Generating Radiations. The AF does not issue permits radiation generating machines, but exposure limits to members of the general public and workers, and controls must be adhered to as specified in AFI 48-148. If an installation does not possess exclusive federal jurisdiction, the state may have regulations that are applicable to machine-generated radiation. In this case, both state and AF Instructions must be met.

#### h. Security Measures for RAM.

(1) General. AF organizations possessing RAM are responsible to provide security for RAM. From a practical standpoint, most RAM is secured in locked cabinets in relatively secure facilities. For larger sources, like those in irradiators, the NRC has more stringent security requirements, with the security for individual sources being evaluated. Large activity source permittees will work directly with AFMSA/SGPR.

(2) Portable Gauges. In 2005, in response to concern over portable gauge security, the NRC required greater security measures for portable gauges. 10 CFR 30.34 states, "each portable gauge licensee shall use a minimum of two independent physical controls that form tangible barriers to secure portable gauges from unauthorized removal, whenever portable gauges are not under the control and constant surveillance of the licensee." The rule is applicable only to specifically-licensed ones, focused primarily on portable density/moisture content gauges like Troxlers<sup>TM</sup>. The rule is also applicable to other gauges like CAMs, ICAMs, ACADAs, M8A1/43A1s, and Niton's<sup>TM</sup> with NRC-licensed byproduct material (usually only those with <sup>241</sup>Am). This new rule is not likely

to have much impact on permittees, since most already store gauges in locked cabinets that are secured in locked rooms.



## 6. Ionizing Radiation Detection and Detection Systems Common to BES

a. General. Radiation detection systems are used for ionizing radiation hazard evaluation and for day-to-day radiation safety in environments with ionizing radiation. Uncertainties in instrument use can be reduced if individuals better understand the characteristics of the emitted radiation, the design of a detection systems, potential radiation absorbers (e.g. air, shielding, source seal, etc.), and the purpose of the measurement. Figure 6-1 contains a generic source-detection system configuration.

(1) Source. The radiation emissions from a source are the most important factor in determining the type of radiation detection system used for a measurement. For RAM or machine-generated radiations with multiple radiation emission types, the mixture can complicate a measurement because some detection systems, while sensitive to many radiation types, are unable to discriminate between different types of radiation. Also, for some mixed radiation type sources where detection is the primary task, it will be easier because more measurement options exist. Source seals, holders, or other materials mated to a source may alter the radiation emitted by a source. For example, in sealed  $\alpha$ -emitting RAM, external  $\alpha$ -radiation emissions are not possible due to the short penetration range of  $\alpha$ -particles (see Table 3-2). The same can be said for sealed  $^{137}\text{Cs}$  and  $^{60}\text{Co}$  sources, where the penetration range of emitted  $\beta$ -particles is less than the thickness of the source encapsulation, and external emissions only include  $\gamma$ -radiation.

(2) Absorbers. Absorber materials can significantly alter the radiation field of a source and affect decisions regarding selection of radiation detection systems. For example,  $^{90}\text{Sr}$  is a pure  $\beta$ -particle emitter, with respective emissions from  $^{90}\text{Sr}$  and its  $^{90}\text{Y}$  daughter being 546 and 2,270 keV (see Table 3-4). If the  $\beta$ -particles are subjected to medium-and high-Z shielding (i.e., materials with medium to high electron density, like many metals), Bremsstrahlung x-rays production can be significant. Like source encapsulation, absorber materials may remove radiation emissions from the radiation field and prevent detection. DU provides a good example to illustrate concepts important to measurement of RAM.

### (3) DU Characteristics and Detection Concepts.

(a) Radiation Emissions. The two most common uses of DU in AF operations are in aircraft counterweights and in 30 mm ammunition, and to a lesser degree in waste from past nuclear weapons maintenance and accident sites. DU consists of tailings from uranium enrichment processes. Over the years of enrichment in the U.S., the isotopic composition of DU has varied significantly and is characterized by the degree of  $^{235}\text{U}$  depletion (i.e., removal or separation from lighter isotopes in uranium like  $^{234}\text{U}$  and  $^{235}\text{U}$ ). DU is commonly described as slightly, moderately, or highly depleted, with the moderately-depleted composition most common. Figure 6-2 provides two bar graphs: one being a mass composition comparison of moderately-depleted and natural uranium, and the other, a similar comparison by mass. For the DU in this example, the  $^{238}\text{U}$  comprises about 84 % of the total uranium activity and about 5.5 times that of the  $^{234}\text{U}$ . Table 6-1 lists the predominant radiation emissions from DU, based on the composition provided in this example. The radioactive emission frequency (percentage) is normalized to the decay of uranium isotopes:  $^{234}\text{U}$ ,  $^{235}\text{U}$ , and  $^{238}\text{U}$ . From the table, it is apparent that DU emits a complex mixture of  $\alpha$ - and  $\beta$ -particles, and photons. A key feature of the  $\gamma$ - and characteristic x-ray (i.e. those from Th, U,

# Detection System

Source

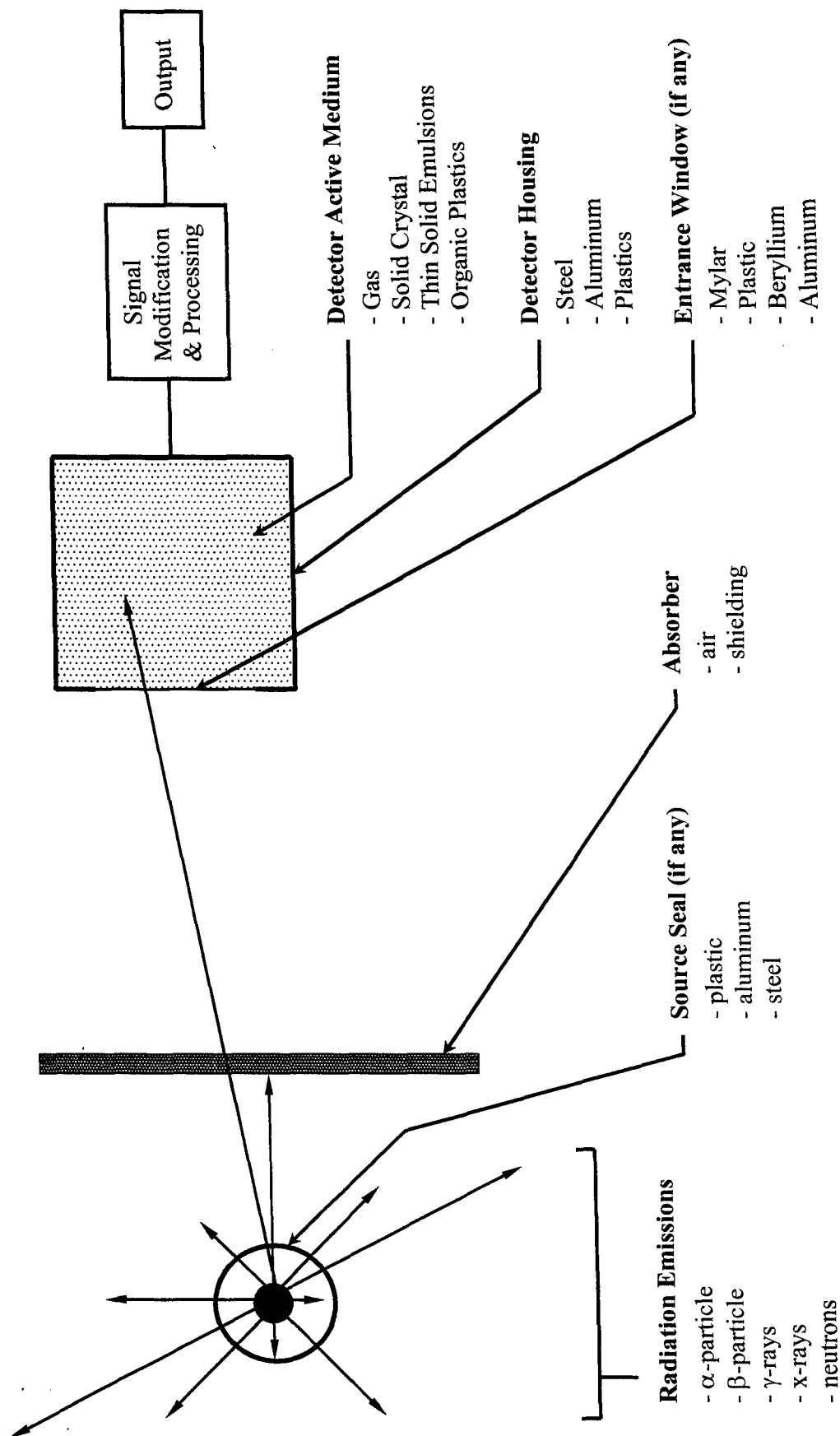


Figure 6-1. Generalized Radiation Detection Configuration.

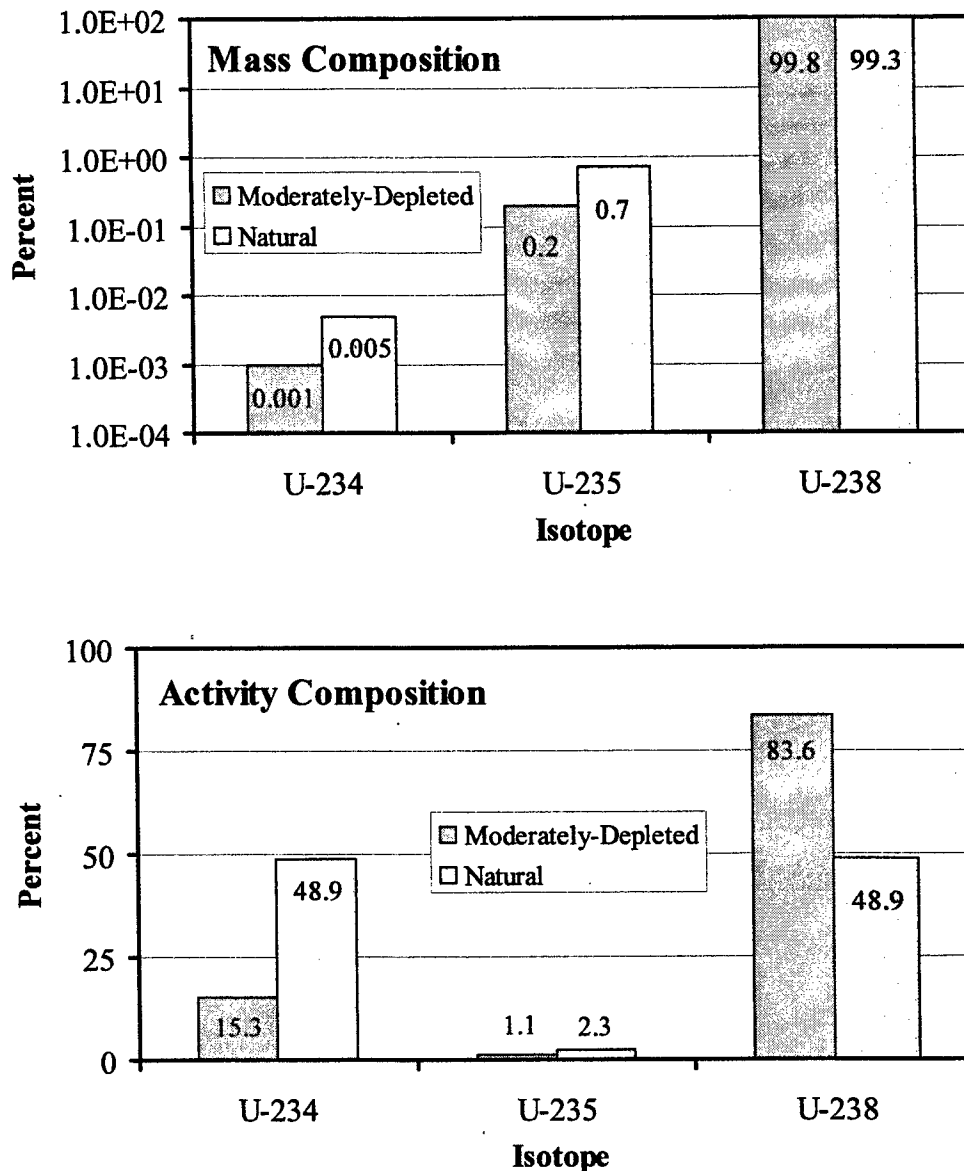


Figure 6-2. Mass and Activity Isotopic Composition of Moderately-Depleted and Natural Uranium.

and Pa) emissions are the relatively low energy and low emission frequency. Bremsstrahlung x-ray production frequency and energy characteristic is highly dependent on the geometry of the uranium. For example, DU in solid metal forms will produce a significant amount of Bremsstrahlung x-rays internal to the metal, due to the high electron density of uranium. While diffusely distributed DU (i.e., in soil), will have relatively low Bremsstrahlung production.

(b) Detection Concepts. AF DU measurement scenarios are varied and subsequently so are the measurement techniques. Table 6-2 lists various DU measurement tasks and radiations available for assessment.

TABLE 6-1. Radiation Emissions from Moderately-Depleted Uranium [Includes Short-Lived Daughters (Those in Equilibrium with Parent)] [Isotopic Composition from Figure 6-2].

$\alpha$ -Emissions		$\beta$ -Emissions		Photon Emissions	
Energy (MeV)	Frequency	Energy (MeV)	Frequency	Energy (MeV)	Frequency
4.20	66 %	2.28*	82 %	0.0926 ( $\gamma$ )	4.7 %
4.15	18 %	0.189	59 %	0.0633 ( $\gamma$ )	4.1 %
4.78	11 %	0.096	21 %	0.1857 ( $\gamma$ )	0.7 %
4.72	4.3 %	0.076	2.3 %	0.1004 ( $\gamma$ )	0.7 %
4.4	0.8 %	0.287	0.5 %	0.1128 ( $\gamma$ )	0.23 %
Blank	Blank	Blank	Blank	0.0532 ( $\gamma$ )	0.02 %
				Th, U, & Pa x-rays	> 10 %
				Bremsstrahlung x-rays	variable

\* most significant source of energetic electrons for Bremsstrahlung x-ray production

For the first four tasks, all emitted radiations are assumed available for detection. For the first two, the tasks are assessment of DU on a surface or a swipe sample. The purpose of both tasks could be designed to meet surface contamination limits or simply determining whether or not contamination exists. Because of low emission frequency and energy of  $\gamma$ -radiations, they are not normally assessed for either task. The  $\alpha$ - and  $\beta$ -assessments have moderate to high detection efficiency, with low to moderate background radiation. In general, due to  $\alpha$ -radiation detection efficiency variations, contamination assessment is more reliable from  $\beta$ -radiation assessment due to its consistent detection efficiency. For the third task, assessing potential DU counterweight covering breaches, while all emissions exist,  $\alpha$ -emissions evaluation is ideal because the surface of an intact counterweight would have very-low background  $\alpha$ -emission, with a breached covering allowing significant detectable  $\alpha$ -emissions. For this case, while detection efficiency can be highly varied, it is of lesser significance since the purpose of the measurement is in simply identification of a breach.

For personnel exposure assessments in DU storage and use areas, unless loose material exists, only  $\beta$ - and  $\gamma$ /x-radiations require evaluation. Assessments are less complex if  $\beta$ -radiations are shielded.

(4) Detection System. Figure 6-1 provides a generic diagram of a detection system. A system contains the detector that has an active medium that, for portable systems, is typically a gas or various types of solids. The detector housing is important in containing, integrity protection of, and shielding some radiations from the active medium. In some cases, the housing is used to produce secondary radiations and thereby increasing the probability for detection of the primary radiation. The signal modification and processing portion of a detection system transforms electrical signals from the detector to usable information and for some systems allows discrimination of detector output signals for many purposes. For example, in detectors that are sensitive to  $\alpha$ - and  $\beta$ -particles, a discriminator may be used to separate signals from the two particles based on the magnitude of detector output, or for  $\gamma$ -spectroscopy systems, allows separation of detection events by the amount of energy deposited in the active medium. Many portable systems have output display

TABLE 6-2. DU Measurement Tasks Common in AF.

Measurement Task	Keys to Radiation(s) for Assessment	
	Emission	Comment
Direct assessment of DU surface contamination	$\alpha$	moderate, but varied (based on surface) detection efficiency; typically low $\alpha$ -background
	$\beta^*$	high, relatively constant detection efficiency; moderate $\beta$ -bkgd
	$\gamma/x$	low, relatively constant detection efficiency; high $\gamma$ -background
Assessment of DU on swipe sample	$\alpha$	moderate, but varied (dependent on swipe material) detection efficiency; typically very-low $\alpha$ -background
	$\beta^*$	high, relatively constant detection efficiency; low $\beta$ -background
	$\gamma/x$	low, relatively constant detection efficiency; low $\gamma$ -background
Assessing potential breach in DU counterweight covering	$\alpha^*$	moderate, but varied (based on surface) detection efficiency; typically low $\alpha$ -background
	$\beta$	high, relatively constant detection efficiency; moderate $\beta$ -bkgd, some metal counterweight coverings may not shield all $\beta$ 's
	$\gamma/x$	emission likely to be the same, regardless of breach
Direct assessment of DU on soil surfaces	$\alpha$	low and highly varied detection efficiency; typically low $\alpha$ -bkgd
	$\beta^*$	moderate, relatively constant detection efficiency; moderate $\beta$ -background
	$\gamma/x$	low, relatively constant detection efficiency; high $\gamma$ -background
Direct assessment of DU at depth in soil	$\gamma/x$	very-low, relatively constant detection efficiency; high $\gamma$ -background
Personnel exposure measurements in DU storage and use areas	$\beta^*$	personnel exposure scenarios require assessment of both radiation emissions; assessment is less complicated if $\beta$ -emissions are shielded
	$\gamma/x^*$	

\* ideal assessment method

with meter movements or digital displays, and for some systems internal storage. One important characteristic of most radiation detection systems is that they are generally responsive to many types of radiation if the radiation is able to deposit energy in the active medium. A radiation detection system's specificity to a particular radiation type is generally made by detector housing design, entrance windows, and signal processing.

#### b. Ion Chambers.

(1) General. The ion chamber is one of the most widely used instruments in the AF for conducting measurement of **exposure from photon radiation fields**. The active volume of ion chambers contains air or specialized gases, like argon, methane, propane, and nitrogen. Ion chambers are in simple terms ion collectors and quantify the number of ion pairs produced in the gas volume by an incident radiation field, where the electric current produced in the active volume is proportional to the incident radiation field. These active volumes are either unsealed, where the pressure and volume composition is dependent on ambient atmospheric conditions, or sealed. The sensitivity of an ion chamber is related to the mass of the gas contained in the active volume, thus

larger detectors and those with greater pressure are more sensitive. Detector active volume housings are commonly constructed of plastics, with some models possessing an "entrance window" that is composed of a lower density thickness material, like mylar. The entrance windows are generally thin enough to allow penetration of most  $\beta$ -particles, except those from  $^3\text{H}$ ,  $^{63}\text{Ni}$ , and  $^{14}\text{C}$ . Some manufacturers claim sensitivity to  $\alpha$ -particles, but usually it is limited to  $\alpha$ -particles with energy higher than those commonly emitted from RAM.

(2)  $\gamma$ -Response. The response of a detector across the range of potential measured photon energies is one of the most important characteristics of an ion chamber. Ideally a flat uniform response is desired, but never attained. Often the region of energy response most critical is low energy photons, where for many systems response is degraded as compared to higher energy photons. This is due to design compromise. For ion chambers of sturdy design and good sensitivity, pressurized active volumes are desired, where the housing is considerable thicker than that of unsealed systems. However, the sensitivity and ruggedness compromise the low energy response. Figure 6-3 contains an energy response plot for the Eberline Model RO-2 unsealed ion chamber,

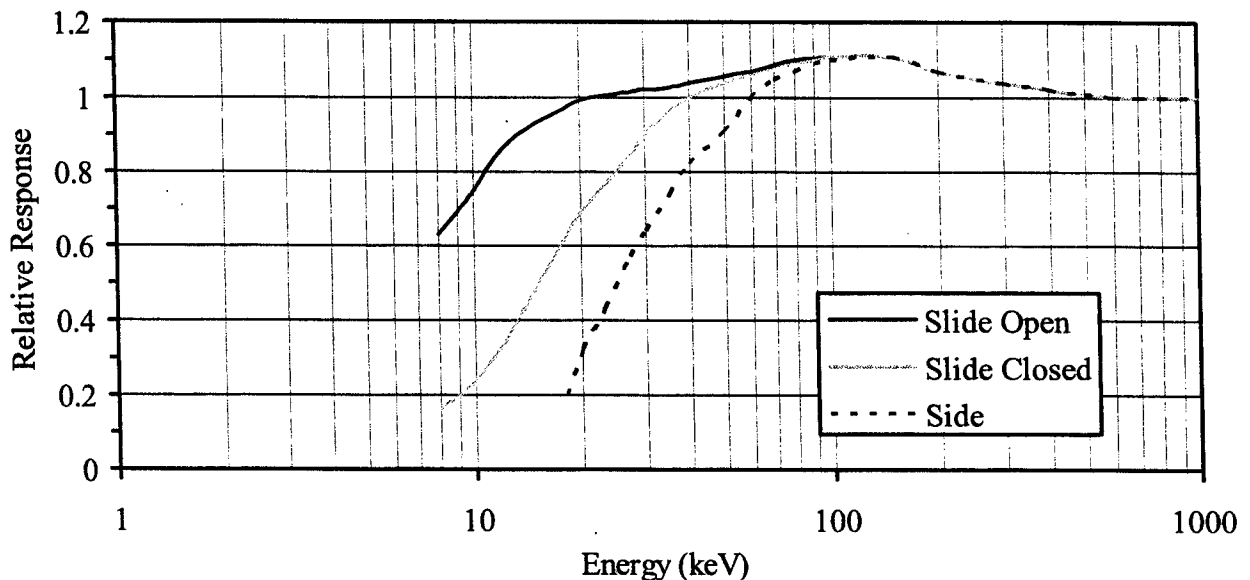


Figure 6-3. Relative Response of an Eberline RO-2 Ion Chamber (Eberline 1983).

based on whether the  $\beta$ -shield slide is open or closed, or if the radiation field is incident to the chamber side. The relative response among the three scenarios is based on differential attenuation of absorbers between the radiation field and the active volume. The  $\beta$ -window has  $7 \text{ mg/cm}^2$  density thickness mylar, the detector wall  $200 \text{ mg/cm}^2$  of phenolic and  $3.4 \text{ mg/cm}^2$  aluminum, the  $\beta$ -shield (covers the  $\beta$ -window)  $400 \text{ mg/cm}^2$  of phenolic, and the instrument case is aluminum. For low-energy photons like that of scattered diagnostic x-rays, it is critical to direct the  $\beta$ -window in the direction of the incident field to ensure adequate response. From the plot, for photon energies above  $100 \text{ keV}$ , the response is relatively uniform regardless of orientation and whether or not the  $\beta$ -shield is open or closed. Figure 6-4 provides the response of two common ion chambers used by BES, the

Victoreen 451B and 451P. The Victoreen devices once carried the Inovision name and are currently manufactured by Fluke Biomedical. The 451B is an unsealed system with a  $\beta$ -shield, similar in to the Eberline RO-2 and newer RO-20, while the 451P is a pressurized system. Clear from the plot is the superior energy response of the 451B in the low-energy region, especially with the  $\beta$ -shield slide open. Appendix A contains energy response plots of other ion chambers used in the AF.

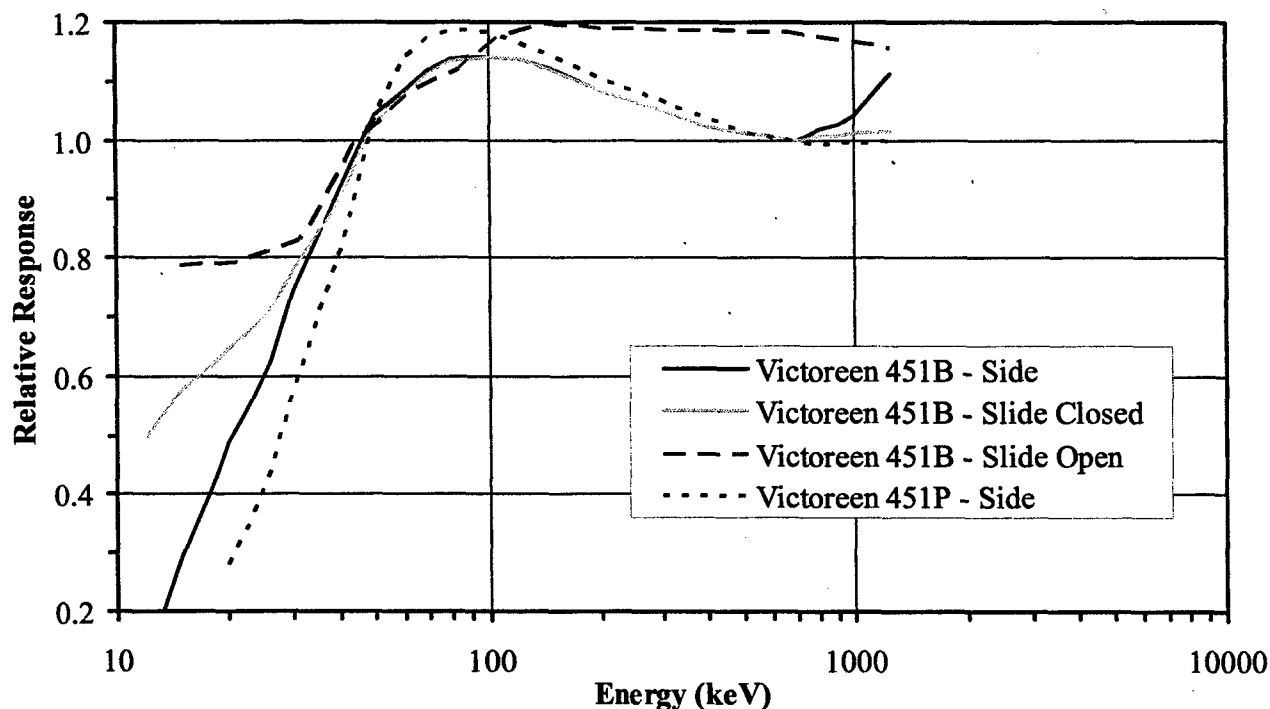


Figure 6-4. Relative Energy Response of the Victoreen 451B and 451P Ion Chambers (Cardinal Health 2003).

Some ion chambers are designed for operation in radio frequency radiation (RFR) environments. Appendix A, Figure A-4 contains an energy response plot for the Victoreen 471RF and 440RF/D, two RF-shielded, unsealed ion chambers that are used in the AF. The energy response for low energy photons is similar to that of the Victoreen 450P, having good response for photon energies greater than 40 keV. Table 6-3 provides specifications for ion chambers commonly used in the AF.

(3) Temperature & Pressure Correction. Because the mass of air in unsealed ion chambers is dependent on ambient temperature and pressure, the response of a detector must be corrected if these parameters are significantly different than that at calibration. Equation 6-1 is used to correct response, where  $CF$  is the correction factor,  $P$  is respective pressure during calibration and ambient at the time of measurement, and  $T$  is temperature in  $^{\circ}K$ . Table 6-4 provides simplified correction factors for pressure,  $CF_P$ , based on mean pressure of various altitudes. Table 6-5 lists temperature correction factors,  $CF_T$ , for combinations of calibration and use temperatures. For measurements requiring both corrections, the overall correction factor is simply the product of the two separate ones. Omission of correction for small differences in temperature and pressure from ambient and calibration are small compared to other measurement uncertainties.

TABLE 6-3. Operation Specifications for Ion Chambers Commonly Used in the AF.

Instrument	Chamber	Modes	Operation Scales	Response Time	$\beta$ -Response	$\beta$ -Window Slide
Eberline RO-2	Unsealed	Rate	0-5, 0-50, 0-500, & 0-5000 mR/hr	5 seconds (0 - 90%)	Yes	400 mg/cm <sup>2</sup> Plastic
Eberline RO-20	Unsealed	Rate	0-5, 0-50, & 0-500 mR/hr 0-5 & 0-50 R/hr	5 seconds (0 - 90 %)	Yes	1,000 mg/cm <sup>2</sup> Plastic
Victoreen 450P	Pressurized	Rate	0-0.5, 0-5, 0-50, 0-500, & 0-5,000 mR/hr	1.8 (0-5 R/hr) to 5 (0-0.5 mR/hr) seconds	Only High Energy (> 1 MeV)	NA
		Integrate	1 $\mu$ R resolution up to 99 R	(10 - 90 %)		
Victoreen 450	Unsealed	Rate	0-5, 0-50, & 0-500 mR/hr 0-5 & 0-50 R/hr	2 (0-50 R/hr) to 8 (0-5 mR/hr) seconds	Yes	200 mg/cm <sup>2</sup> Aluminum
		Integrate	10 $\mu$ R resolution up to 999 R	(10 - 90 %)		
Victoreen 451P (Inovision 451P)	Pressurized	Rate	0-0.5, 0-5, 0-50, 0-500, & 0-5,000 mR/hr	1.8 (0-5 R/hr) to 5 (0-0.5 mR/hr) seconds	Only High Energy (> 1 MeV)	NA
		Integrate	1 $\mu$ R resolution up to 99 R	(10 - 90 %)		
Victoreen 451B (Inovision 451B)	Unsealed	Rate	0-5, 0-50, & 0-500 mR/hr 0-5 & 0-50 R/hr	2 (0-50 R/hr) to 8 (0-5 mR/hr) seconds	Yes	440 mg/cm <sup>2</sup> Plastic
		Integrate	10 $\mu$ R resolution up to 999 R	(10 - 90 %)		
Victoreen 470A	Unsealed	Rate	0-3, 0-10, 0-30, 0-100, 0-300, & 0-1000 mR/hr	1.5 (0-300 mR/hr) to 8 (0-3 mR/hr) seconds	Only Medium & High (> 120 keV)	NA
		Integrate	0-3, 0-10, 0-30, 0-100, 0-300, & 0-1000 mR			
Victoreen 471RF	Unsealed	Rate	0-1, 0-3, 0-10, 0-30, 0-100, & 0-300 mR/hr	1.5 (0-300 mR/hr) to 8 (0-3 mR/hr) seconds	Only Medium & High (> 200 keV)	NA
		Integrate	0-1, 0-3, 0-10, 0-30, 0-100, & 0-300 mR			
Victoreen 440RF/D	Unsealed	Rate	0-1, 0-3, 0-10, 0-30, & 0-100 mR/hr	5 (0-100 mR/hr) to 7 (0-1 mR/hr) seconds	Only Medium & High (> 150 keV)	NA



$$CF = \frac{P_{Cal} T_{Amb}}{P_{Amb} * T_{Cal}}$$

Equation 6-1

TABLE 6-4. Pressure Correction Factors,  $CF_p$ , Based on Mean Pressure at Various Altitudes.

		Altitude When Calibrated (feet)										
		0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
Altitude When Used (feet)	0	1	0.969	0.938	0.907	0.876	0.844	0.813	0.782	0.751	0.720	0.689
	1000	1.032	1	0.969	0.938	0.907	0.876	0.844	0.813	0.782	0.751	0.720
	2000	1.066	1.032	1	0.969	0.938	0.907	0.876	0.844	0.813	0.782	0.751
	3000	1.103	1.066	1.032	1	0.969	0.938	0.907	0.876	0.844	0.813	0.782
	4000	1.142	1.103	1.066	1.032	1	0.969	0.938	0.907	0.876	0.844	0.813
	5000	1.184	1.142	1.103	1.066	1.032	1	0.969	0.938	0.907	0.876	0.844
	6000	1.230	1.184	1.142	1.103	1.066	1.032	1	0.969	0.938	0.907	0.876
	7000	1.278	1.230	1.184	1.142	1.103	1.066	1.032	1	0.969	0.938	0.907
	8000	1.331	1.278	1.230	1.184	1.142	1.103	1.066	1.032	1	0.969	0.938
	9000	1.389	1.331	1.278	1.230	1.184	1.142	1.103	1.066	1.032	1	0.969
	10000	1.452	1.389	1.331	1.278	1.230	1.184	1.142	1.103	1.066	1.032	1

(4)  $\beta$ -Response. While the primary use of ion chambers in the AF is in exposure measurements of photon radiation fields, many detectors have active volume housings that are sufficiently thin and/or have windows that allow the penetration of  $\beta$ -particles. While the output response of ion chambers are usually in exposure or exposure rate (R, R/hr, or multiples of these), the response from  $\beta$ -particle interactions does not have a practical meaning since the unit of exposure is only applicable to the ionization of air by photons. Therefore, when using these detectors in a radiation field comprised of photons and  $\beta$ -particles, some caution must be made in interpretation of the results. For detectors with  $\beta$ -windows, an instrument's response to the  $\beta$ -radiation field can usually be determined by making a measurement with and without the  $\beta$ -window covered, or by collecting one of the measurements with the  $\beta$ -window oriented away from the incident  $\beta$ -field. Some ion chambers have been evaluated for response to  $\beta$ -radiation fields. Table 6-6 lists the response in reported exposure rate per dose rate for three  $\beta$ -radiation fields. For the  $^{90}\text{Sr}/^{90}\text{Y}$  source, the response of the three example detectors has a response in terms of exposure nearly equivalent to the absorbed dose. For the lower energy  $\beta$ -emitters, the response per absorbed dose is significantly lower, with the reduction due to the greater degree of attenuation by the active volume housing. In use of correction factors like these, caution should be exercised if the energy of the  $\beta$ -radiation is not known.

(5) Modes of Operation. Two modes of operation are used for ion chambers commonly used in the AF: rate and integrate modes. For most constant radiation fields that are emitted by RAM and long-exposure, radiation-generating machines, rate mode will be used.

TABLE 6-5. Temperature Correction Factors,  $CF_T$ , in Degrees Fahrenheit.

		Temperature When Calibrated ( $^{\circ}\text{F}$ )					
		40	50	60	70	80	90
Temperature When Used ( $^{\circ}\text{F}$ )	-10	0.90	0.88	0.87	0.85	0.83	0.82
	0	0.92	0.90	0.88	0.87	0.85	0.84
	10	0.94	0.92	0.90	0.89	0.87	0.85
	20	0.96	0.94	0.92	0.91	0.89	0.87
	30	0.98	0.96	0.94	0.92	0.91	0.89
	40	1	0.98	0.96	0.94	0.93	0.91
	50	1.02	1	0.98	0.96	0.94	0.93
	60	1.04	1.02	1	0.98	0.96	0.95
	70	1.06	1.04	1.02	1	0.98	0.96
	80	1.08	1.06	1.04	1.02	1	0.98
	90	1.10	1.08	1.06	1.04	1.02	1
	100	1.12	1.10	1.08	1.06	1.04	1.02
	110	1.14	1.12	1.10	1.08	1.06	1.04

TABLE 6-6.  $\beta$ -Radiation Response of Various Ion Chambers to Various  $\beta$ -Sources (Schleien 1992).

	Energy (keV)		
	$^{90}\text{Sr}/^{90}\text{Y}$	$^{204}\text{Tl}$	$^{147}\text{Pm}$
Maximum Beta Energy (keV)	546, 2270	766	224
Average Beta Energy (keV)	196, 934	244	62
Instrument	Response (mR/hr per mrad/hr in air)		
Eberline RO-2	1.0	0.45	0.12
Victoreen 470A	1.10	0.79	0.10
Victoreen 471RF	0.80	0.33	0.02

For measurements of pulsed fields, common to medical x-ray and some research emitters, use of integrate mode is necessary because the **response time of most detection systems in rate mode is insufficient for accurate measurements**. Integrate mode accumulates the charge collected in an ion chamber over long periods of time. For instruments that count interactions by number, the integrate mode in these instruments is more commonly called "scalar." From Table 6-3, the response time of example instruments range from 1.8 to 8 seconds. Figure 6-5 provides a depiction of the response of an ion chamber to a 30 millisecond (ms) duration pulsed and continuous field. From the figure, it is assumed that the fields have a magnitude of 90 mR/hr and the instrument has a 2.2 s response time (10 – 90 % full-field). From the plot, the peak instrument response to the pulsed field is about 2.7 mR/hr, over 30 times lower than the peak field strength. When using the integrate mode, it is important that the instantaneous exposure rate does not exceed the maximum dose rate of the instrument. If the peak exposure rate is exceeded, the displayed response will be lower than the actual field strength. Table 6-7 lists the maximum exposure rate of the ion chambers listed in Table 6-3. For others, refer to the user's manual prior to survey measurements.

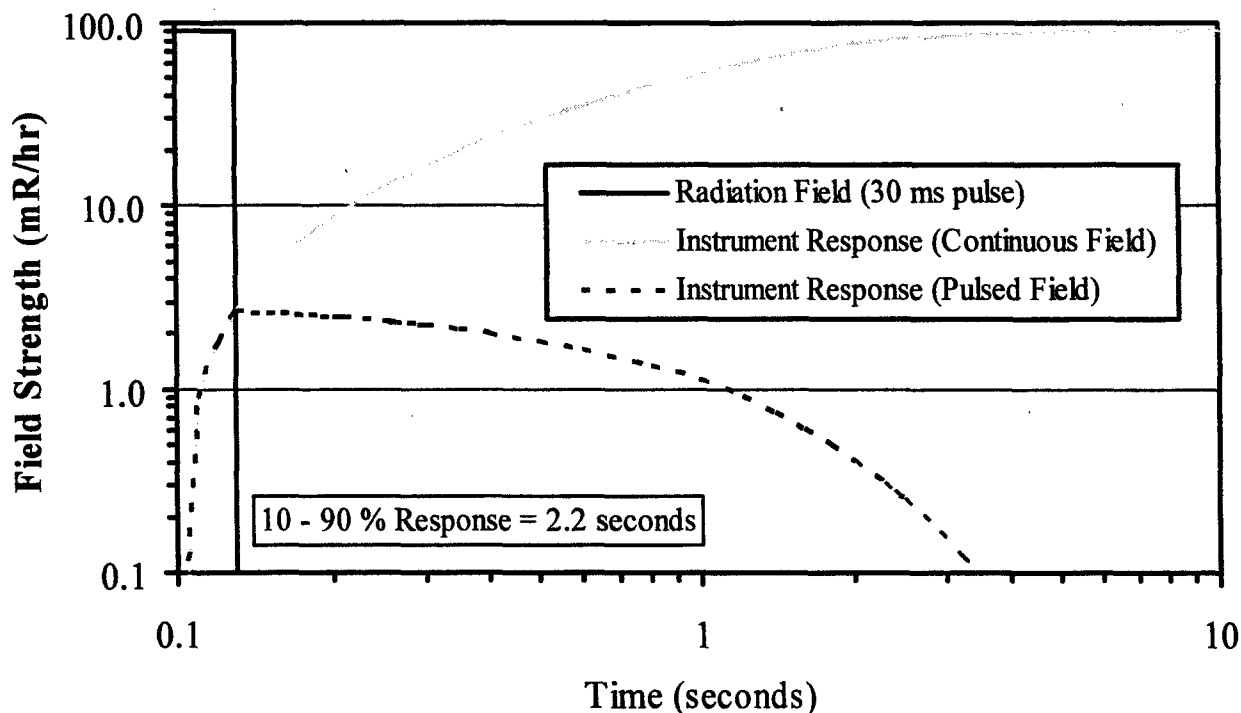


Figure 6-5. Example Illustration of Instrument Response to a Pulsed and Continuous Field.

Table 6-7. Maximum Exposure Rate of Ion Chambers from Table 6-3.

Instrument	Maximum Exposure Rate (R/hr)
Victoreen 450P & 451P	5
Victoreen 450 & 451B	50
Victoreen 470A	1000
Victoreen 471RF	300

(6) Ion Chamber Use in AF Radiation Measurements. Table 6-8 lists some recommended uses of ion chambers in AF radiation environments. The table lists the most common measurement tasks and recommended ion chamber(s) or equivalent. For the cases where two system types are listed, the hierarchical preference is by order, though either system type would meet the basic survey need. It is important to note for measurements of exposure in the primary beam [most commonly conducted for medical systems to assess beam quality and entrance skin exposure (ESE)], most BES do not possess the proper instruments for these surveys. AFIOH, Regional Medical Physics Support, and biomedical equipment technician (BMET) sections have appropriate instruments for these surveys.

TABLE 6-8. Ion Chamber Recommended Uses in AF Radiation Measurements.

Measurement Task	Recommended Ion Chamber(s)	Notes	Mode
General radiation exposure measurements of RAM storage and use areas	1. Victoreen 451B (or equiv.) 2. Victoreen 451P (or equiv.)	1, 2	Rate
General radiation exposure measurements in diagnostic x-ray use areas (scatter)	1. Victoreen 470A (or equiv.) 2. Victoreen 451B (or equiv.) 3. Victoreen 451P (or equiv.)	3	Integrate
General radiation exposure measurements in mammography use areas (scatter)	1. Victoreen 470A (or equiv.) 2. Victoreen 451B (or equiv.)	3	Integrate
Radiation exposure measurements in x-ray primary beam (Beam Quality, ESE)	Specialized (see AL/OE-TR-1997-0162)	4	Integrate
General radiation exposure measurements in NDI operations (primary & scatter)	1. Victoreen 451P (or equiv.) 2. Victoreen 451B (or equiv.)	2	Rate
High-radiation exposure dose-reconstruction measurements in NDI operations (primary & scatter)	1. Victoreen 451P (or equiv.) 2. Victoreen 451B (or equiv.)	5	Integrate
General radiation exposure measurements in research accelerator & x-ray environments	Victoreen 471RF (or equiv.)	6	Rate Integrate
General radiation x-ray exposure measurements from RFR emitters	Victoreen 471RF (or equiv.)	6	Rate
DOT dose equivalent rate compliance measurements	1. Victoreen 451P (or equiv.) 2. Victoreen 451B (or equiv.)	2	Rate
General radiation exposure measurements at radioactive material burial sites	1. Victoreen 451B (or equiv.) 2. Victoreen 451P (or equiv.)	1, 2	Rate

## Measurement Notes:

1. Mixed  $\gamma/\beta$ -radiation field with high-energy  $\beta$ -particles can perturb photon exposure measurements. Assess potential for mixed field. Shield for  $\beta$ -radiation (if necessary) for accurate exposure measurements. Assess  $\beta$ -radiation dose from other method or known  $\beta$ -radiation conversion factor.
2. Pressurized ion chambers usually have better sensitivity to low-exposure rate photon fields.
3. Unsealed ion chambers usually have a more uniform energy response in low-energy photon fields.
4. BES will not normally maintain this type of measurement system. AFIOH, Medical Physics, and Regional BMET possess these instruments.
5. Due to potentially high radiation fields, remote measurements may be indicated.
6. Potential for RFR radiation interference in generic ion chamber.

c. Geiger-Mueller (GM) Detectors.

(1) General. Like the ion chamber, G-M detectors are commonly used in AF for radiation measurements. G-M detectors, like ion chambers, have gas as an active volume. The most important difference, however, is the bias potential applied across the anode and cathode. For ion chambers, the bias potential is sufficiently high to allow ion drift and limit recombination losses. Whereas, in a G-M detector, bias potentials are significantly higher and accelerated ions produce a cascade of additional ion pairs. Regardless of the initiating ionizing event or magnitude (i.e., a  $\beta$ - or  $\gamma$ -particle interaction) the number of ion pairs produced is constant. Advantages of G-M detectors

over ion chamber are the high sensitivity, low cost, and ruggedness. These detectors are sealed and contain similar gases to pressurized ion chambers, except that they contain quenching gases, that aid performance at high count rates. There are two common design styles: the long cylindrical and short cylindrical (called a "pancake"). Like ion chambers, many are designed with  $\beta$ -windows that allow detection of  $\beta$ -particles in addition to photons. Figure 6-6 depicts common styles.

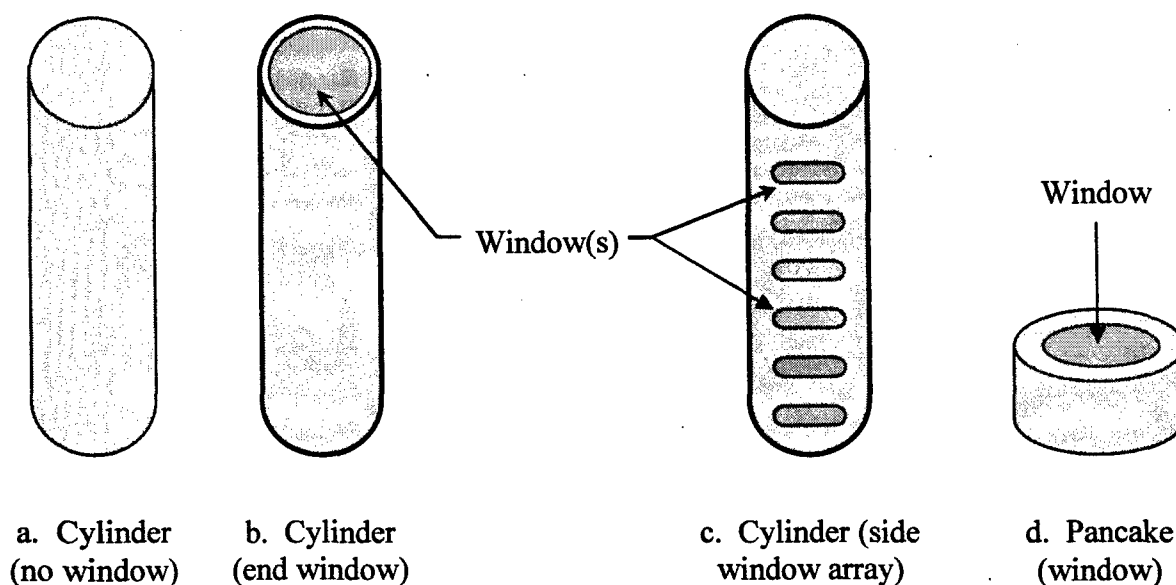


Figure 6-6. Styles of G-M Detectors Commonly Used in the AF.

(2)  $\gamma$ -Response. In general, G-M detectors are counting devices, where the magnitude of the charge produced in the active volume is independent of energy deposited by the initiating particle interaction. Thus, these devices are not, in general, designed to provide a uniform response across a broad range of energies in terms of radiation exposure. Figure 6-7 provides a plot of energy response for the Eberline E-112B G-M detector that has a design of Figure 6-6c. From the figure, apparent is the gross over-response for low-energy photons. This characteristic is common for G-M detectors that are constructed of metal housings, as the metal housings have a significantly higher probability for interaction with low-energy photons than other materials that better simulate the atomic structure of air (that radiation exposure is based on). While not displayed here, the AN/PDR-27T G-M survey meter has this characteristic as well, though it has an end window design shown in Figure 6-6b. The AN/PDR-27T was commonly used by the AF in the past.

More recently there have been efforts to improve the design of G-M tubes to provide a more uniform relative response to energy for radiation exposure. The ADM-300 that AF organizations currently use is fitted with two internal G-M detectors: one large volume detector with a removable-shield end window for  $\beta$ -particles that covers the low radiation field range, and a small volume detector that covers the high radiation field range. Figure 6-8 shows the relative energy response of these two internal detectors with respect to radiation exposure. In comparison to other G-M's, the response characteristics of the low-range detector are quite good, and on par with some ion chambers.

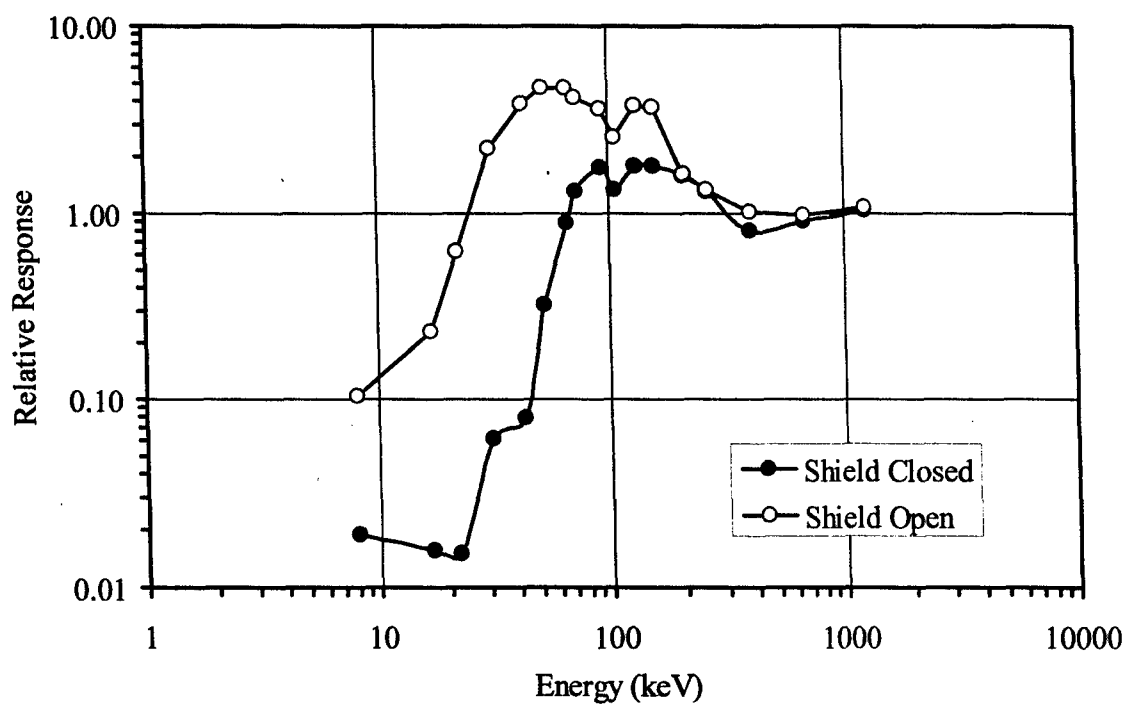


Figure 6-7. Relative Energy Response of Eberline E-112B G-M Survey Meter for Exposure, Normalized to Cs-137 (Storm *et al* 2003).

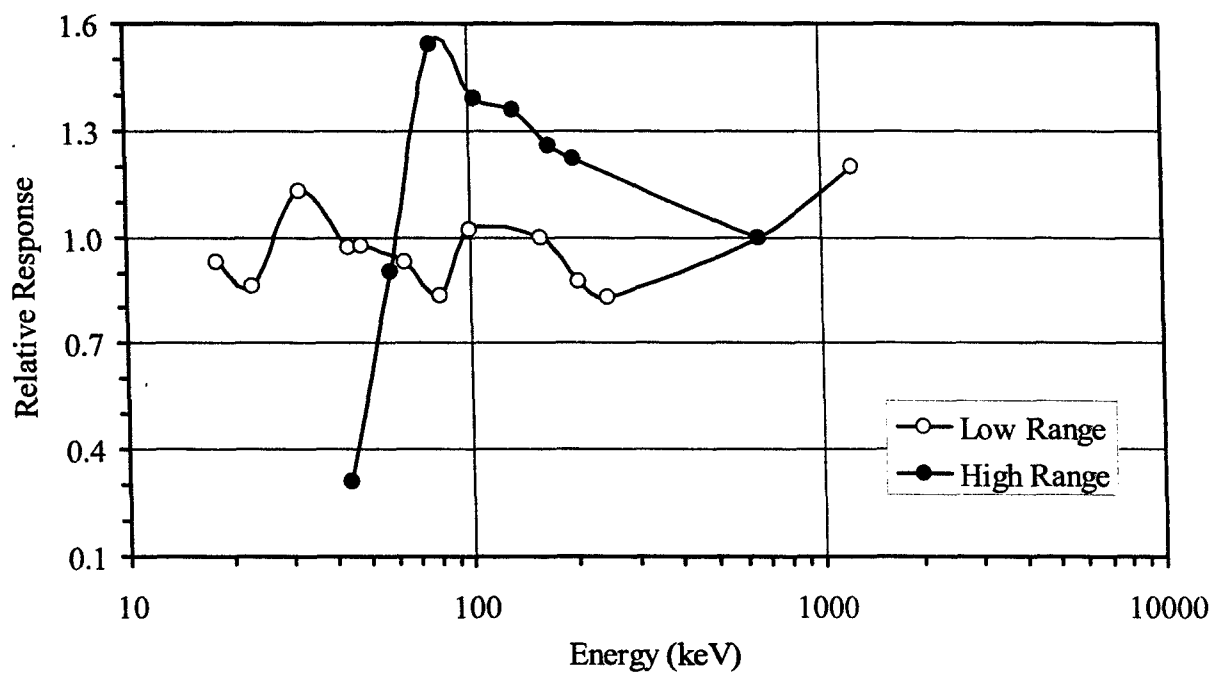


Figure 6-8. Relative Energy Response of ADM-300 Internal G-M Detectors for Exposure, Normalized to Cs-137 (Canberra 2004).

For the detector fitted into the ADM-300 metal case, there will be some low-energy degradation if the end window  $\beta$ -shield is closed. In the past, the AF has frowned on the use of G-M detection systems for radiation exposure measurements, primarily due to the non-uniform energy response. However, for low-range measurements (10  $\mu$ R/hr to 5 R/hr), the ADM-300 internal probe is recommended for general survey measurements where dose assessments are required. Ludlum Measurements, Inc produces the Model 44-38 Energy-Compensated G-M that has a style like Figure 6-6c and a relatively uniform energy response that is plotted in Appendix A, Figure A-5. Table 6-9 lists the specifications for the internal and external G-M tubes incorporated into the ADM-300.

TABLE 6-9. Operation Characteristics of ADM-300 G-M Probes (NRC Industries 1991).

Detector	Style	Operation Scales	$\beta$ -Window	$\beta$ -Window Shield
Internal Low-Range	Cylindrical End Window	10 $\mu$ R/hr – 5 R/hr	3 - 4 mg/cm <sup>2</sup>	~ 850 mg/cm <sup>2</sup>
Internal High-Range	Cylindrical No Window	5 R/hr – 10K R/hr	None	NA
“Gamma” BGP-100 Low-Range	Cylindrical End Window	10 $\mu$ R/hr – 5 R/hr	3 - 4 mg/cm <sup>2</sup>	~ 850 mg/cm <sup>2</sup>
“Gamma” BGP-100 High-Range	Cylindrical No Window	5 R/hr – 10K R/hr	None	NA
“Beta” BP-100	Pancake	Automatic $\gamma$ - Compensation	9.9 – 10.3 mg/cm <sup>2</sup>	None

(3)  $\beta$ -Response. Due to the relatively high sensitivity to energy deposition events, regardless of the magnitude, they are highly effective for detection of  $\beta$ -particles, if they are fitted with  $\beta$ -windows. For cylindrical designs, it is an effective measurement technique to perform measurements in potentially-mixed,  $\beta$ - and  $\gamma$ -radiation fields with the  $\beta$ -shield open and closed. The difference in the net instrument response is equivalent to the  $\beta$ -particle contribution, except for mixed fields where a significant fraction of the photon field is comprised by low-energy photons, like that from medical x-ray machines and characteristic x-rays from RAM. In these cases, the  $\beta$ -shield is effective at attenuating most  $\beta$ -particles and low-energy photons. While the pancake style probe is sensitive to  $\gamma$ - and  $\beta$ -radiations, it is most effectively used for frisking (i.e., search) for previously unidentified  $\beta$ -contamination, due to the relatively high  $\beta$ -window area to detector volume ratio. Some pancake probes are made with very thin entrance window ( $\sim 0.5$  mg/cm<sup>2</sup>) that are effective for  $\alpha$ -particle detection. However, since the ADM-300 has a probe specially designed for  $\alpha$ -particles and other  $\alpha$ -measurement systems are available for use, the AF does not recommend using pancake G-M probes for  $\alpha$ -particle measurements. Table 6-10 lists manufacturer provided detection efficiencies for the ADM-300, BP-100 probe, and two other commonly used pancake probes. Efficiencies are listed for many  $\beta$ -particle emitters in order of increasing  $\beta$ -particle spectral energy. From the table, the Ludlum and Bicon detectors have very similar efficiencies for the common isotopes evaluated. However, the BP-100 used on the ADM-300 has an efficiency similar to the other two for  $^{90}\text{Sr}/^{90}\text{Y}$ , but is significantly lower for  $^{14}\text{C}$ . This is due to the significantly higher  $\beta$ -window density thickness of the BP-100 as compared to the other two. Another difference

between the BP-100 and the other detectors listed is that the BP-100 has an automatic  $\gamma$ -exposure compensation, provided by the internal G-M probes. This feature effectively lowers the reported count rate in the BP-100 Beta Probe for photon radiations. The feature can be disabled if desired.

TABLE 6-10. Detection Efficiency ( $4\pi$ ) and Other Specifications for Pancake Probes Commonly Used in the AF (NRC 1991, Ludlum 2005, Cardinal Health 2003, and Bicon 1996).

Parameter	Units Isotope	ADM-300 BP-100	Ludlum Model 44-9	Victoreen 489-110	Bicon PGM
$\beta$ -Window Density Thickness	mg/cm <sup>2</sup>	9.9 – 10.3	1.4 – 2.0	1.5 – 2.0	1.4 – 2.0
$\beta$ -Window Area	cm <sup>2</sup>	15.5	15	15	15.5
Dead Time	$\mu$ s	NL	80	NL	50
Detection Efficiency ( $4\pi$ ) per $\beta$ - or $\gamma$ -Emission (As Applicable)	<sup>14</sup> C	0.001	0.05	0.05	0.05
	<sup>147</sup> Pm	NL	NL	NL	0.1
	<sup>60</sup> Co*	0.06	NL	NL	NL
	<sup>99</sup> Tc	NL	0.19	0.12	0.15
	<sup>137</sup> Cs*	0.15	NL	0.24	NL
	<sup>36</sup> Cl	NL	NL	0.26	NL
	<sup>90</sup> Sr/ <sup>90</sup> Y	0.23	0.22	0.29	0.23
	<sup>32</sup> P	NL	0.32	NL	NL
	<sup>241</sup> Am ( $\gamma$ -only)	0.003**	0.002**		
	<sup>60</sup> Co ( $\gamma$ -only)	0.005**	0.005**		

\* Emits  $\gamma$ -radiation as well.

\*\* Measured at Brooks City-Base

NL = Not Listed

(4) Pancake Probe Uses. Pancake probes have many uses in AF operations. Among them, perhaps the most important is frisking personnel, equipment, and other potentially contaminated surfaces for  $\beta$ -particle and photon emissions. They are commonly used in:

- (a) Nuclear Medicine,
- (b) on radiological incident/accident response teams, and
- (c) in laboratories that handle unsealed RAM.

For BES, they are commonly the best instrument available to meet:

- (d) DOT surface contamination limits discussed in para. 5.e.3) and listed in Table 5-8,
- (e) surface contamination limits and screening levels discussed in para. 5.d, and
- (f) air sample filter assessment requirements for  $\beta$ -particle emitting RAM.



For the latter two applications, regulatory entities may require the samples to have additional evaluation by an approved laboratory. As illustrated in Figure A-6 for the Victoreen 489-110, pancake probes have non-uniform energy response.

(5) Unknown  $\beta$ -Particle Identification. For discrete samples, like air filter samples and wipe samples that have  $\beta$ -emitting RAM, portable pancake G-M detectors can be used to assess the approximate energy spectra of the emitter(s) through a simple method of collecting multiple measurements of the source (i.e., filter) through varying layers of paper absorber. Figure 6-9 contains example measurements collected by the author at Wright-Patterson AFB with National Institute of Standards and Technology (NIST) traceable sources. From the plot, it is fairly easy to assess half-value layers or another index that differentiates the relative energy spectra of the  $\beta$ -emitter. It is important to note that this technique is useful in estimating the energy spectra of an unknown. Some factors may confound this simple field technique: a contaminant that has multiple  $\beta$ -emitters and differences among BP-100 probe  $\beta$ -window density thicknesses.

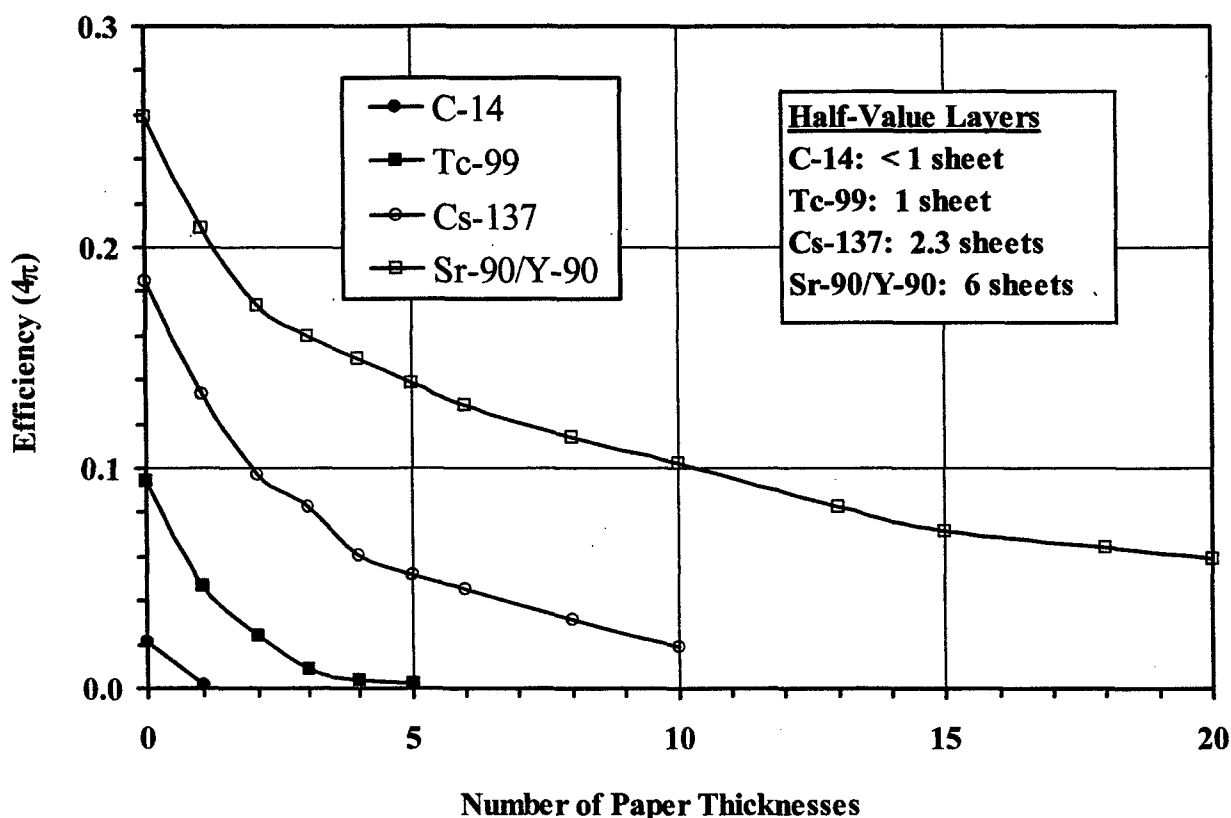


Figure 6-9. Measured Detection Efficiency of Four  $\beta$ -Particle Emitters (Small Plated Sources) vs. Varying Thickness of Post-it<sup>®</sup> Paper with ADM-300 (BP-100 Probe) [<sup>®</sup>Trademark of 3M].

(6) Calibration. G-M probes are commonly calibrated to a  $\gamma$ -radiation source like  $^{137}\text{Cs}$  and/or to a pure  $\beta$ -particle. If a probe-meter combination is used for regulatory compliance measurements, it must be calibrated to the type of radiation being measured. Usually energy-compensated G-Ms are calibrated to  $\gamma$ -sources, since their primary purpose is in assessment of

radiation exposure, while regulatory compliance measurements performed by pancake G-Ms are usually for  $\beta$ -particle radiations, or mixed  $\beta/\gamma$ -fields. For  $\beta$ -particle calibrations, there are two primary types of calibration sources: small and large area sources that simulate semi-infinite planes. Most small area sources have diameters about 2 to 3 cm in diameters. Calibrations with this type of source is useful for measurements of wipe and leak test samples, whereas large area calibrations are useful for measurements on large area surfaces like those in facility decommissioning or from spills.

d.  $\alpha$ -Particle and  $\alpha/\beta$ -Particle Scintillators.

(1) General. Scintillation detectors are one of the basic detector designs that have been used for decades. The basic design of a scintillator detector system is shown in Figure 6-10. Energy from an ionizing radiation is deposited into the scintillator material that converts a part of the energy to light that is proportional to the energy deposited. The light is converted to an electrical signal and amplified in the photomultiplier tube. The signal, dependent on the type of detection system, can be analyzed according to the pulse height or simply counted according to events that meet a specified pulse height discrimination level.

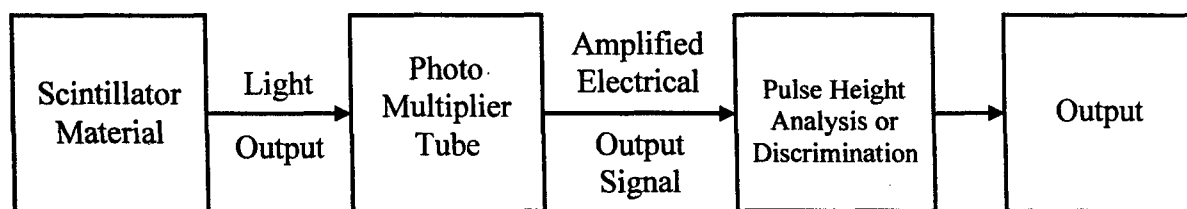


Figure 6-10. Basic Scintillator Detector Design.

$\alpha$ -particle systems commonly use thin films of mylar that are coated with ZnS(Ag) scintillator material.  $\alpha/\beta$ -particle systems usually have a mylar coated ZnS(Ag) that is backed by a plastic scintillator, designed to absorb energy from  $\beta$ -particles.

(2) Instrument Specifications. Table 6-11 contains specifications for some common  $\alpha$ - and  $\alpha/\beta$ -particle detectors used in the AF. Among the four systems listed, only the Ludlum 43-89 is designed for detection of both  $\alpha$ - and  $\beta$ -particles. From the table, the two Ludlum detectors and AP-100 probe on the ADM-300 have similar detection efficiencies for  $\alpha$ -particles from  $^{239}\text{Pu}$ . These three detectors have window areas about 100 cm<sup>2</sup> and represents an area commonly been used for compliance. Figure A-8 provides a conceptual bar graph of factors affecting detection efficiency.

(3)  $\alpha$ -Particle Detection Efficiency. The principal factors in detection efficiency for  $\alpha$ -particles are discussed below.

(a) Surface Condition. The condition of the surface containing the source of  $\alpha$ -particles is critical to detection efficiency. Commonly, detection efficiencies are determined in the laboratory with sources that have RAM plated on a metal surface. For these sources, a high fraction of the  $\alpha$ -particles that are emitted in directions away from the metal surface, have the potential for detection.

TABLE 6-11.  $\alpha$ - and  $\alpha/\beta$ -Particle Scintillator Instrument Specifications  
(NRC 1991, Ludlum 2005, Cardinal Health 2003, and Bicron 1996).

Parameter	Units Isotope	ADM-300 AP-100	Ludlum 43-90	Ludlum 43-89	Victoreen 489-60
Window Density Thickness	mg/cm <sup>2</sup>	0.5	0.8	1.2	3
Window Area: Total (Active)	cm <sup>2</sup>	123 [113]* (92)	125 (100)	125 (100)	NL (11.4)
Plastic Scintillator	mm	NA	NA	0.25	NA
Detection Efficiency (4 $\pi$ ) per Particle	<sup>239</sup> Pu or <sup>238</sup> Pu (S)	0.18	0.20	0.19**	0.13
	<sup>239</sup> Pu or <sup>238</sup> Pu (L)	0.15	NL	0.15**	NL
	<sup>99</sup> Tc-99 ( $\beta$ )	NA	NA	0.10	NA
	<sup>90</sup> Sr/ <sup>90</sup> Y ( $\beta$ )			0.17	
	<sup>241</sup> Am ( $\gamma$ -only)			0.002**	
	<sup>60</sup> Co ( $\gamma$ -only)			0.005**	

\* Measured entrance windows: outside metal-mesh flange - 129 cm<sup>2</sup>,  
(Sheely 2005) mylar foam gasket - 119 cm<sup>2</sup>,  
ZnS foam gasket - 113 cm<sup>2</sup>

\*\* Measured at Brooks City-Base  
S = small area source  
L = large area source

For measurements of RAM contamination on a paper filter, a high fraction of the particles emitted in a direction away from the paper will be attenuated by the paper surface, reducing detection efficiency. In a comparison test conducted by the author at Wright-Patterson AFB on NIST traceable sources: one on filter paper and one plated on metal, and with a Ludlum 43-89 and an ADM-300 AP-100, measurements on the filter paper source had detection efficiencies only about 40% of the source plated on metal. For measurements on surfaces like concrete, asphalt, or soil, detection efficiency will be significantly lower than that for sources on filter paper. In addition, detection efficiency will be higher for small area sources (i.e., the source is dimensionally smaller than the detector entrance window) as compared to large area sources. From some examples of Table 6-11, large area efficiencies are about 20 % lower than small area ones.

(b) Detector-to-Source Distance. The distance between the detector and source impacts detection efficiency for  $\alpha$ -particles. From Table 3-2,  $\alpha$ -particles only have penetration ranges in air of a few centimeters, thus if the detector entrance window is not close to the source, detection efficiency can be significantly degraded. In addition, for small area sources, with detector to source geometry changes, a greater fraction of the emitted particles will not have a trajectory that intercepts the entrance window, further degrading detection efficiency.

(c) Window Density Thickness. The density thickness of the entrance window impacts detection efficiency. For the detectors listed in Table 6-11, entrance windows are mylar, which is flexible, strong, and light opaque. For a <sup>239</sup>Pu  $\alpha$ -particle, as listed in Table 3-2, the penetration range is 4.2 mg/cm<sup>2</sup>, significantly greater than the window density thickness of the ADM-300 AP-100, and Ludlum 43-90 and 43-89 probes. However, it is not much greater than that of the Victoreen 489-60, which in part explains the lower detection efficiency of this detector compared to the others. There are practical limits on the minimum thickness of the mylar, since it is easily

damaged by routine use (e.g., blades of grass, blowing sand). Small holes in the mylar can render the detector inoperable, since ambient light can enter the detector chamber and create false detection events. Therefore, for use on surfaces that have the potential to damage the mylar, users will have to strike a balance between keeping detection efficiency high and limiting the potential for damage. The mylar can be checked for damage by directing it in close proximity to a light source and monitor instrument response. Light leaks can be repaired in the field with black lacquer. A good rule of thumb is to limit repaired areas to less than 10 % of the total area, with mylar replacement for damage beyond this.

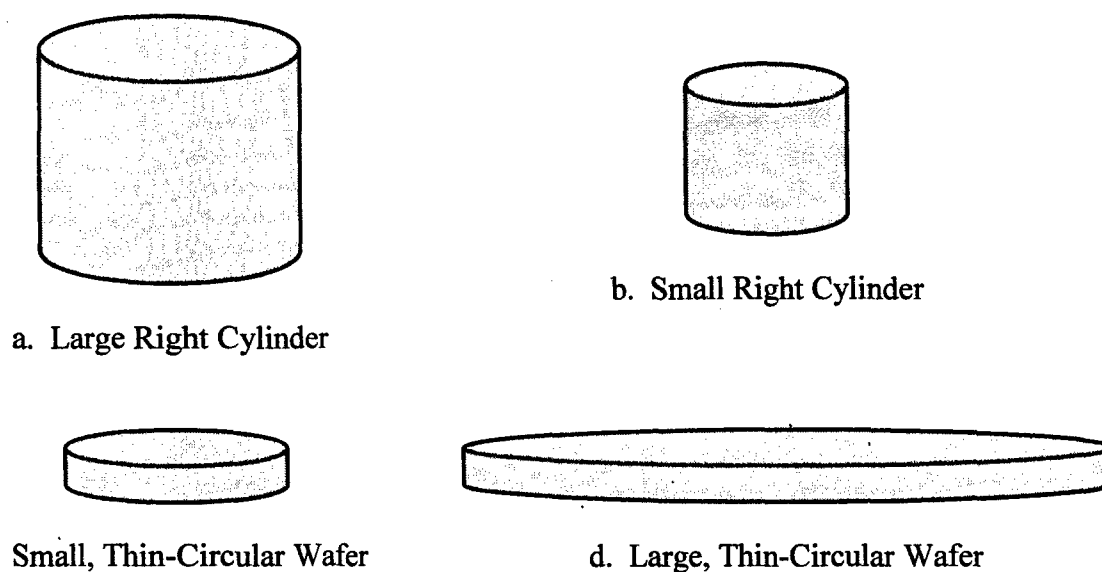
(d) Window Area Active Fraction. Most of these detection systems have protective metal grids that cover the mylar. The fraction of the detector entrance window encompassed by the grid is effectively a dead area since  $\alpha$ -particles striking it will not be detected. As noted on Table 6-11, the area of the detector encompassed by the grid is the difference between the total and active window area.

(e) Pulse Height Threshold. The electronic pulse height threshold used in these systems is important in discriminating particle interactions in the active volume(s) by magnitude. As noted in para. 6a.3d), active volumes are generally sensitive to many radiation types. This is true for the ZnS(Ag) and plastic scintillators in these systems. Because the ZnS(Ag) and plastic scintillators are very thin in these systems, photon radiations have a low probability of interaction.  $\alpha$ - and  $\beta$ -particle interactions are effectively separated by magnitude, with the higher energy deposition events being from  $\alpha$ -particles and the lower primarily from  $\beta$ -particles. For systems designed for  $\alpha$ -detection only, the selection of energy threshold is a compromise. If the threshold is set low, detection efficiency will be higher for  $\alpha$ -particles, but there will be some undesired potential for  $\beta$ -detection, termed "cross-talk." For higher thresholds, cross-talk can be effectively eliminated, but at an expense to detection efficiency.

#### e. NaI(Tl) and CaF<sub>2</sub>(Eu) Scintillator Detectors.

(1) General. Thallium-drifted sodium-iodide [NaI(Tl)] and europium-drifted calcium-fluoride CaF<sub>2</sub>(Eu) crystalline detectors have the same basic system design illustrated in Figure 6-10. This class of detectors is generally used for photon detection and spectroscopy, but will respond to  $\beta$ -particle interactions if the crystalline detector's housing is sufficiently thin to allow penetration. Figure 6-11 contains the geometry of four commonly used systems and Figure 6-12 contains specifications for systems commonly used in the AF.

(2) Energy Response. The primary factors in energy response of these detectors is based on the crystalline detector housing composition and window composition, if a detector has one, and the geometry of the crystal. In general, good response to low-energy photons requires thin detector housings and/or windows that are comprised of low atomic number (Z) materials like plastics, beryllium, etc. Also, good high-energy photon response is achieved by detectors of long lengths in three dimensions, like the large right cylindrical design of Figure 6-11a. The detectors shown in Figure 6-11a and b are specially designed for detection and spectroscopy of low-energy photons. These detectors will have good response to low-energy photons provided that they are fitted with low-Z, thin windows. Because the crystals are thin, the response to medium- to -high energy photons is poor (i.e., they mostly pass through the crystal without interacting), which greatly limits

Figure 6-11. Styles of NaI(Tl) and CaF<sub>2</sub>(Eu) Scintillator Detectors Commonly Used in AF.TABLE 6-12. Specifications of NaI(Tl) and CaF<sub>2</sub>(Eu) Scintillator Detectors Commonly Used in AF.

System	Style (Fig. 6-11)	Dimensions	Window	Detector Housing	Common Use
Ludlum 19 μR Meter	(b) NaI(Tl)	1" diameter 1" tall	None	Aluminum	Counting Low-Level Photon Radiation
ADM-300 XP-100 X-Ray Probe	(c) CaF <sub>2</sub> (Eu)	1.4" diameter 3 mm thick	12 mg/cm <sup>2</sup> & wire screen	Aluminum	Low-Energy Photon Detection
BNC SAM Model 935	(a) NaI(Tl)	2" diameter 2" tall	None	Plastic	Low to High Energy Photon Spectroscopy
Thermo Electron identiFINDER	(b) NaI(Tl)	1.2" diameter 1.5" tall	None	Plastic	Low to Moderately-High Energy Photon Spectroscopy
Exploranium IDENTIFIER	(b) NaI(Tl)	1.5" diameter 2.2" tall	None	Aluminum	Low to High Energy Photon Spectroscopy
Canberra InSpector	(c) NaI(Tl)	1.5" diameter 1.5" tall	None	Aluminum	Low to High Energy Photon Spectroscopy
Eberline PG-1	(c) NaI(Tl)	2" diameter 1 mm thick	7 mg/cm <sup>2</sup> Al & wire screen	Aluminum	Low Energy Photon Detection & Spectroscopy
Bicron G5 "FIDLER"	(d) NaI(Tl)	5" diameter 1.6 mm thick	47 mg/cm <sup>2</sup> beryllium	Aluminum	Low Energy Photon Detection & Spectroscopy
Eberline SPA-3	(a) NaI(Tl)	2" diameter 2" tall	None	Aluminum	Moderately-Low to High Energy Photon Detection & Spectroscopy

the deposition of energy in the low-energy spectral region from Compton scattering of medium- to high-energy photon interactions. In contrast, some right cylindrical designs, while fitted with low-Z, thin windows that allow good response to low-energy photons, will have high background count rates in the low-energy spectral region from Compton scattered high energy photons interactions. Therefore, the advantage of the thin crystal detectors over others for low-energy photons is the greatly reduced background.

(3) Scintillators Used by BES. While Figure 6-12 lists scintillators used in the AF, there are a few that are more commonly used by BES, justifying further discussion.

(a) ADM-300, XP-100, "**X-Ray Probe**." The XP-100 is a  $\text{CF}_2(\text{Eu})$  probe that is used on the ADM-300. Of all the external probes used on the ADM-300, this probe is most commonly misapplied to measurements. The probe was specifically designed to measure low-energy photons emitted by weapons-grade plutonium (WGP), and has the pulse height setting calibrated to quantify detection frequency of photons from 8.5 to 25.5 keV. However, many BES personnel inappropriately use it to measure pulsed medical x-ray fields. When attached to the ADM-300, the output units are counts/minute (cpm), microcuries per square-centimeters ( $\mu\text{Ci}/\text{cm}^2$ ), or disintegrations/square-centimeter ( $\text{d}/\text{cm}^2$ ). For the latter units, the assumption is that the source is  $^{241}\text{Am}$ , with the source being 3 cm from the detector entrance window. Currently, the AF only calibrates the energy window, but does not perform an absolute detection efficiency calibration for this system. Thus, the instrument response in terms of  $\text{d}/\text{cm}^2$  or  $\mu\text{Ci}/\text{cm}^2$  is not valid, and the instrument is only useful for relative, indication-only measurements.

(b) Ludlum Model 19. The Ludlum Model 19 is a low-level photon field meter that may be used by BES. The instrument has five measurement scales: 0 – 25, 0 – 50, 0 – 250, 0 – 500, and 0 – 5000  $\mu\text{R}/\text{hr}$ . While this instrument has greater sensitivity to low-level photon fields than the ion chambers used in AF operations, it has drastic over-response to low-energy fields as compared to its response to  $^{137}\text{Cs}$ , the common calibration energy (Figure 6-12). Because of the non-uniform response across the range of photon energies and good response of energy-compensated G-M detectors, like that of the ADM-300, its use for radiation exposure measurements is not advised. BES is not commonly required to measure exposure rates below those that can be measured by the ADM-300 low-range internal G-M, making the Ludlum Model 19 unnecessary for most BES.

(c) BNC SAM Model 935. The SAM Model 935 was a recent addition to BEE Weapons of Mass Destruction First Responder's equipment authorization. This instrument's primary purpose is photon spectroscopy for identification of unknown RAM. These small and portable  $\text{NaI}(\text{Tl})$  spectroscopy systems are common today for accident/incident response. Two other similar instruments, the Thermo Electron identiFINDER and Exploraneum IDENTIFIER, are listed in Table 6-12. All of these systems have software algorithms that aid the user in identification of unknowns. Users should be aware that proper interpretation of spectra from these systems is an acquired skill and software algorithms may not correctly identify radionuclides due to practical limits in radionuclide library content and interferences. Also, interpretation of spectra can be aided by additional information like the presence of  $\alpha$ - and/or  $\beta$ -particle emissions from the unknown RAM, and when applicable the approximate  $\beta$ -particle energy spectra. These concepts will be discussed later in this report.

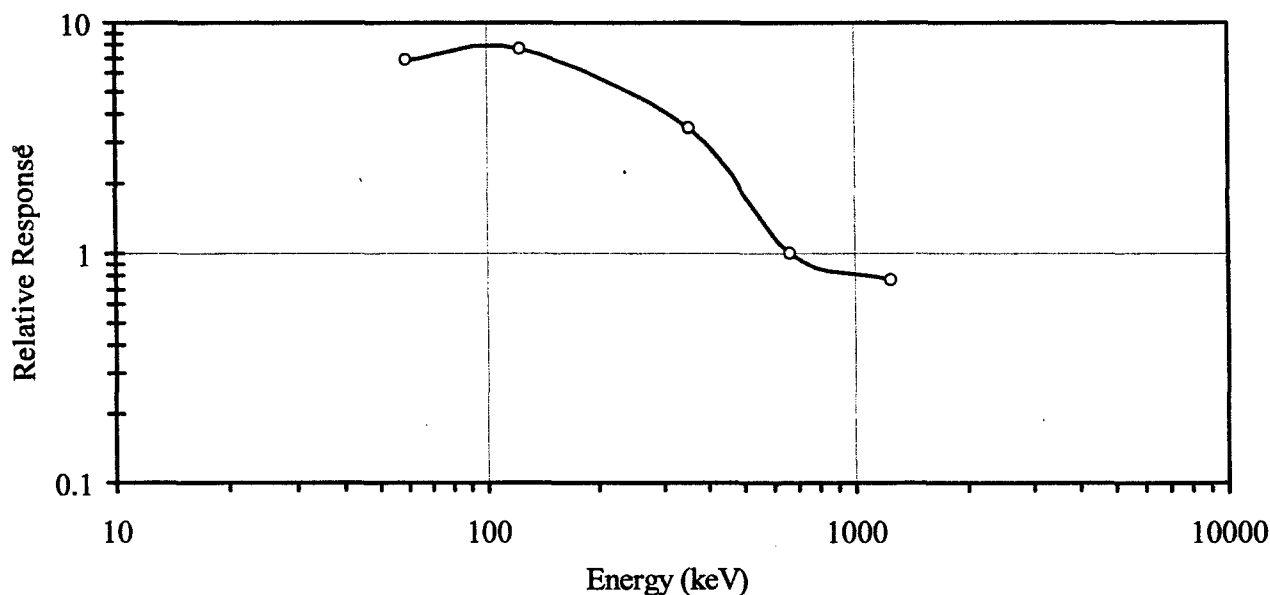


Figure 6-12. Relative Energy Response of the Ludlum Model 19 Micro R Meter (Ludlum 1997).

(d) Field Instrument for Detection of Low-Energy Radiations (FIDLER). The FIDLER is a specialized NaI(Tl) detector that is used for detection and spectroscopy of low-energy photons. The detector was first developed for use with WGP, but is useful for any low-energy photon because of the thin, low-Z window and thin crystal that inherently has low background count rates. While most BES will not have one of these systems, in the event of a WMD or nuclear weapons accident where WGP exists, these devices will be used extensively. AFIOH/SDR maintains numerous instruments of this type in its consulting function and unit type code (UTC) teams in the Air Force Radiation Assessment Team (AFRAT).

#### (4) Example Energy Spectra and Instrument Channel Settings.

(a) Ra-226. Figure 6-13 contains a photon emission spectrum from  $^{226}\text{Ra}$  collected on a SPA-3 NaI(Tl) with a multi-channel analyzer. Table 6-13 contains a list of radiation emissions from  $^{226}\text{Ra}$  and daughters products. From the figure, the prominent "peaks" in the spectrum are labeled according to the source of the emission. The peaks correspond well to the photon emission energies and frequencies as listed in the table. This emission spectrum is similar to those that can be acquired on the SAM 935. The characteristic x-rays, centered around 75 keV, are not listed in the table, but are a complex mixture primarily from bismuth and secondarily polonium. Characteristic x-rays may not be listed in standard libraries of instruments like the SAM 935 and these spectral peaks could be attributed to a radionuclide that may not present in the sample (i.e., false identification). Users should be cautious in applying the results of systems that identify radionuclides based on spectral peaks in the region encompassed by x-ray from heavy atoms (i.e., 70 – 100 keV) when heavy radionuclides (i.e., radium, thorium, bismuth, etc.) have been identified in the spectra.

(b) Instrument Channel Settings. Many portable NaI(Tl) and  $\text{CaF}_2(\text{Eu})$  detectors are not used with meters that have multi-channel analyzers. Rather they are used with one (1) or a few single pulse-height analysis (PHA) channels. These instruments can only provide count rate or

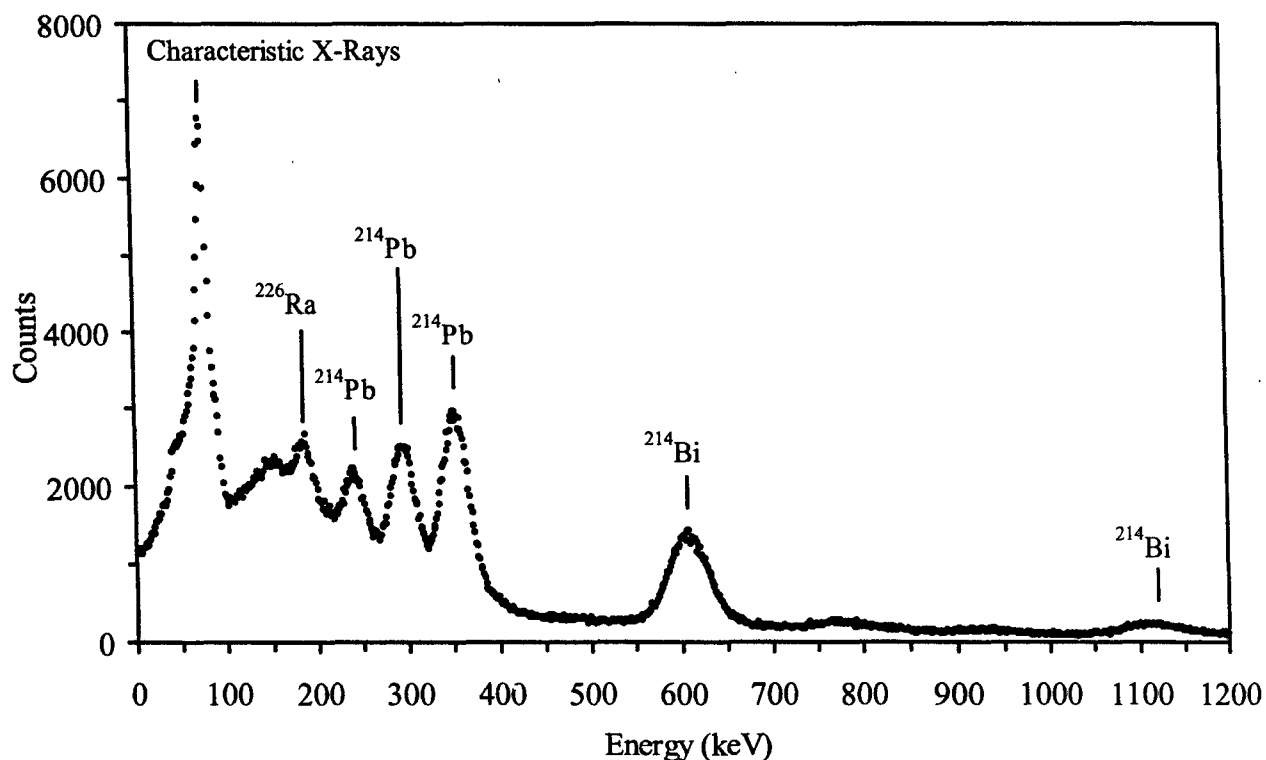


Figure 6-13. Photon Emission Spectrum from  $^{226}\text{Ra}$  Collected on a SPA-3 NaI(Tl).

TABLE 6-13. Radiation Emissions from  $^{226}\text{Ra}$  and its Daughter Products (Primary Chain Only).

Radionuclide	Half-Life	α-Emissions		β-Emissions		Photon Emissions	
		Energy (MeV)	Frequency	Energy (MeV)	Frequency	Energy (MeV)	Frequency
<sup>226</sup> Ra	1602 yrs	4.78	94 %	None		0.186	3.6 %
		4.60	6 %				
<sup>222</sup> Rn	3.82 days	5.49	100 %	None		Negligible	
<sup>218</sup> Po	3.05 min	6.00	100 %	Negligible		None	
<sup>214</sup> Pb	26.8 min	None		0.65	50 %	0.242	7.5 %
				0.71	40 %	0.295	19 %
				0.98	6 %	0.352	36 %
						0.786	1.1 %
<sup>214</sup> Bi	19.7 min	Negligible		1.0	23 %	0.609	47 %
				1.51	40 %	1.12	17 %
				3.26	19 %	1.764	17 %
<sup>214</sup> Po	164 μsec	7.69	100 %	Negligible		Negligible	



integrated count information on energy deposition events that occur within the channel set by the user. Figure 6-14 contains the  $^{226}\text{Ra}$  spectrum from Figure 6-13 with different PHA options. In the case of gross mode, in this example, photon interactions that have energy deposition greater than 50 keV will be counted, while interactions with lower energy will not be recorded. The lower energy discriminator for many commercially available systems is normally referred to as the "threshold setting." For the broad single channel analysis case, the threshold setting is the same as gross mode, however, photon interactions with energy deposition greater than about 490 keV, for this example, are not recorded. The energy range of the channel is commonly termed the "window." The last case is for a fairly narrow window centered about the 609 keV peak from  $^{214}\text{Bi}$ . In this case, only energy deposition events that occur within this limited energy range will be recorded. For many systems, the user must set the threshold, and select a window width, or operate in gross mode. In gross mode, all events with energy deposition above the threshold will be recorded. Some systems, like the XP-100 probe on the ADM-300, has a narrow single channel that is set during calibration, as noted in para. 6.e.3)a). The choice of settings will depend on the measurement task. When the isotope being measured is known, measurements can be optimized by setting a single channel and lower the sensitivity of the system to the target photon or photon range. However, when unknowns are involved, gross mode is commonly used to ensure that photon emissions are not omitted.

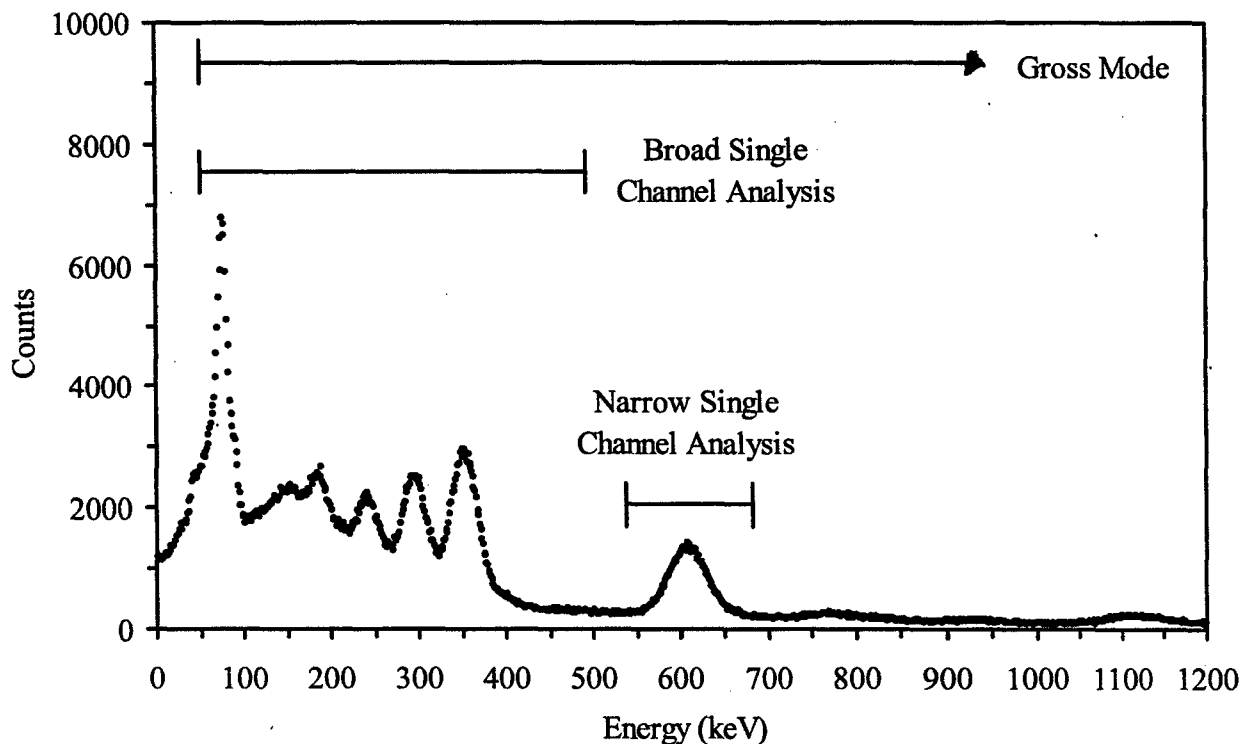


Figure 6-14.  $^{226}\text{Ra}$  Photon Emission Spectrum with Details on Different Pulse-Height Analysis Options.

(c) Depleted Uranium. Figure 6-15 contains two photon emission spectra from DU with a FIDLER probe; one unshielded and one shielded by 3/8 inch plastic. For the unshielded spectrum,

three spectral peaks are identified by markers at the approximate center of each peak. The inset box lists the approximate energy of each peak center and photons that contribute to each peak. Table 6-1 lists radiation emissions from DU and will aid in interpretation of the spectra. The highest energy peak noted is for the combination of photons from the 92.6 keV  $\gamma$ -ray and thorium (Th), uranium (U), and protactinium (Pa) x-rays. It is interesting to note that the x-rays have a larger contribution to the peak, as compared to the  $\gamma$ -ray. As well, the peak centered at 66.1 keV has a contribution from the 63.3 keV  $\gamma$ -ray and an iodine escape from photons of energy centered around 94.1 keV. Iodine escape peaks are a common feature of NaI(Tl) FIDLER detectors. These peaks are formed when a photon excites an iodine K-shell electron, but when the electron cascade produces a K to L-shell transition x-ray, the x-ray escapes the detector volume, and the energy deposited is decreased by about 29 keV. In this example, this feature added to a peak that had a similar energy, skewing

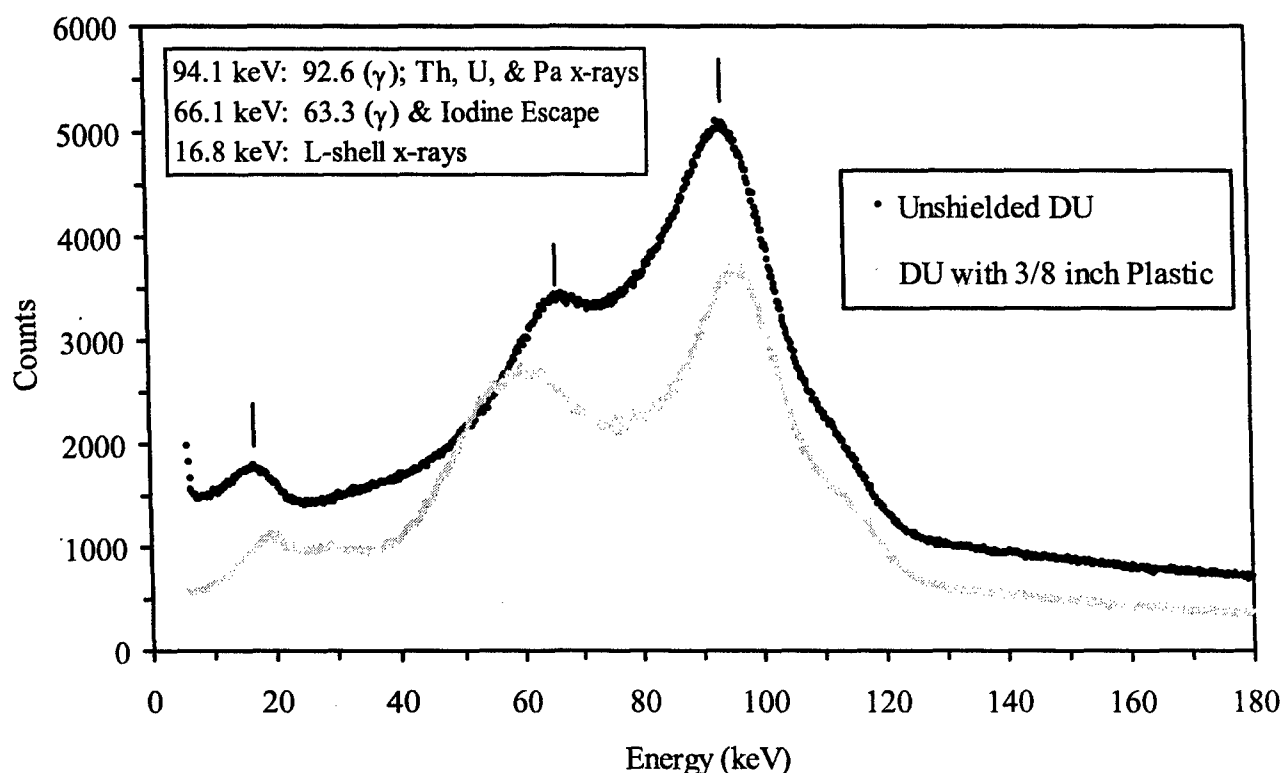


Figure 6-15. Photon Emission Spectrum from DU Collected on a BICRON Model G5 NaI(Tl) [FIDLER].

the spectral peak center by about 3 keV. For other radionuclides, this detector feature may add a spectral peak, where a previous peak did not exist, lending to speculation of the existence of another radionuclide. Another important point of discussion regarding Figure 6-15 is comparison of the unshielded and shielded spectra. In general, it is apparent that the shielded spectrum has a lower number of overall counts because the shield has effectively absorbed many of the photon emissions. For some photons, however, Compton scattering occurs rather than complete absorption. This is evidenced by enhanced deposition of photons with energies in the 60 keV region. Therefore, while example spectra for particular radionuclides, whether they are collected with a FIDLER, SAM 935,

etc., the geometry of the source or shielding may alter the relative shape of spectra. Actual spectra collected in the field may not closely resemble laboratory examples, even if for the same detection system. Figure A-9 and A-10 contain DJU spectra collected with a SPA-3 and Canberra INSPECTOR, respectively. Because the SPA-3 has an aluminum housing, it affords much greater attenuation of low-energy photons than the FIDLER that has a beryllium window. Also, comparing the two spectra, the one collected on the SPA-3 has a significantly diminished 63 keV peak and an unidentifiable L x-ray peak. Likewise, the spectrum collected on the INSPECTOR has an unidentifiable L x-ray peak, but retains good detail on the 63 keV peak.

(d) Cs-137. Figure 6-16 contains a photon emission spectrum from  $^{137}\text{Cs}$  collected on a SPA-3 NaI(Tl).  $^{137}\text{Cs}$  has a simple photon emission scheme, but has a number of features on the spectrum that are worthwhile discussing to better understand  $\gamma$ -spectroscopy systems. The full-energy peak corresponds to the 661.7 keV  $\gamma$ -ray emitted by  $^{137\text{m}}\text{Ba}$ , while the peak at about 32 keV is from barium x-rays. The other two peaks are important features. The Compton edge is the maximum energy possible for a Compton-scattered, photon interaction in the detector. The backscatter peak is caused by energy deposition events from the primary source (661.7 keV) that have first interacted by a Compton scattering event in material surrounding the detector. Both features are commonly observed in spectrum, but can be misinterpreted by inexperienced personnel.

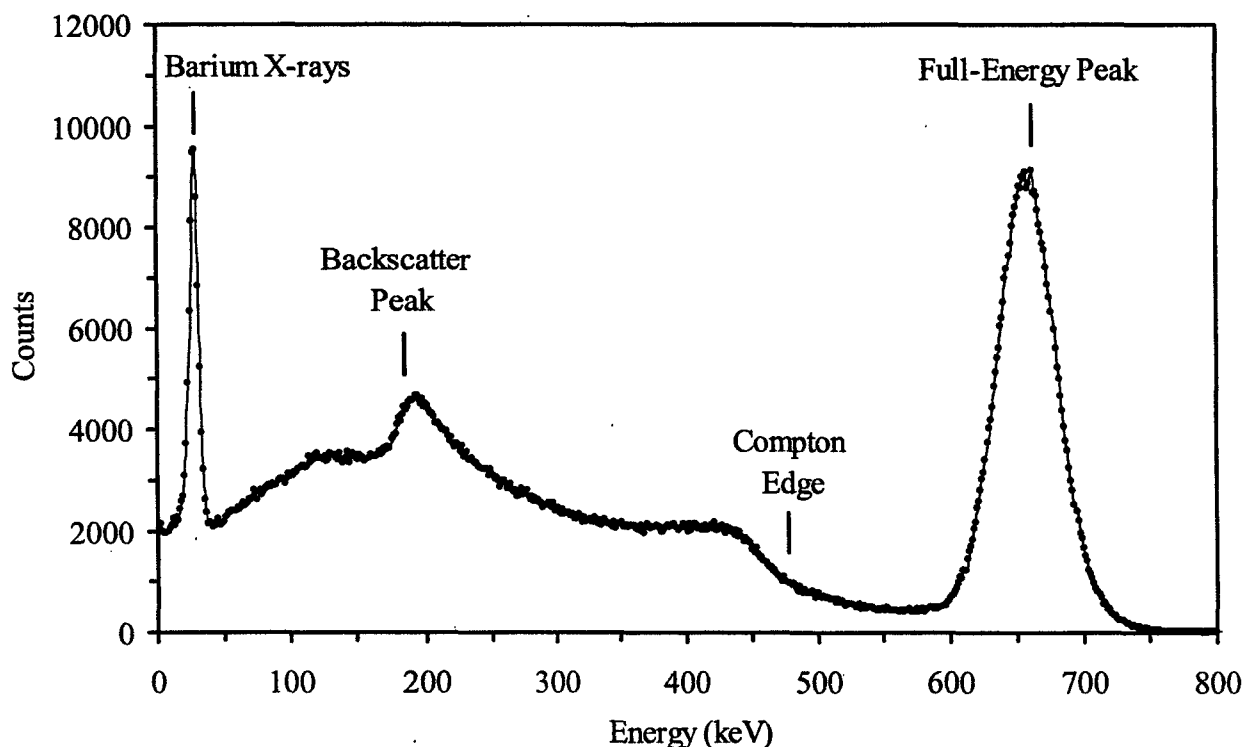


Figure 6-16. Photon Emission Spectrum from  $^{137}\text{Cs}$  Collected on a SPA-3 NaI(Tl).

f. Neutron Detection Instrumentation.

(1) General. Few BES shops possess neutron detection systems because there is little operational need. Among the sources of neutrons, the only sources that would commonly be evaluated by BES are portable moisture density gauges, with Troxler Model 3400 series being the most common. The ADM-300 has an optional Model NP-100 neutron probe, but this probe is not part of standard AF ADM-300 kits. Table 6-14 lists specifications for three neutron probes that are commonly used in the AF. From the table, all are responsive to neutrons ranging from thermal to fast energies. All neutron measurements systems have a highly varied energy response and must be calibrated to a neutron field that has an energy distribution similar to that being quantified.

(2) Radiation Fields from Troxler 3400 Series. Troxler 3400 Series gauges contain sealed  $^{137}\text{Cs}$  and  $^{241}\text{Am:Be}$  sources, producing external  $\gamma$ - and neutron radiations. Tables 6-15 and -16 contain measured radiation profiles from the manufacturer for Models 3430 and 3440. The tables

TABLE 6-14. Operation Characteristics of Neutron Probes  
Used in AF (NRC Industries 1991 & Ludlum 2005a & b).

Probe	Type	Neutron Range	Dose-Equivalent Range
ADM-300 NP-100	$\text{BF}_3$	thermal to 15 MeV	0 – 20 rem/hr
Ludlum Model 42-9	$\text{BF}_3$	thermal to 8 MeV	0 - ~8 rem/hr
Ludlum Model 42-5	$^6\text{LiI}(\text{Eu})$	thermal to 12 MeV	Meter-Specific

TABLE 6-15. Radiation Profile for Troxler Model 3430 Gauge (RRSSD 2001).

Location	Surface			10 cm			30 cm			1 meter		
	$\gamma$	$\eta$	$\gamma+\eta$	$\gamma$	$\eta$	$\gamma+\eta$	$\gamma$	$\eta$	$\gamma+\eta$	$\gamma$	$\eta$	$\gamma+\eta$
Gauge Alone (mrem/hr)												
Front	13	1.7	14.7	5	1.7	6.7	1.1	0.3	1.4	0.3	<0.1	0.3
Back	26	1.4	27.4	8	1.4	9.4	2.5	0.5	3.0	0.4	<0.1	0.4
Left	13	0.5	14	4	0.5	4.5	0.7	0.25	0.95	0.1	<0.1	0.1
Right	12	0.7	13	8	0.7	8.7	2.5	0.25	2.75	0.4	<0.1	0.4
Top	19	1.7	20.7	8	1.7	9.7	0.6	0.7	1.3	0.15	0.1	0.25
Bottom	18	6.0	24	2.5	6	8.5	0.6	0.9	1.5	0.1	0.1	0.2
In Plastic Transport Case (mrem/hr)												
Front	10	0.7	10.7	5	0.7	5.7	1.2	0.4	1.6	0.25	<0.1	0.25
Back	7	0.8	7.8	3	0.8	3.8	0.8	0.25	1.1	0.1	<0.1	0.1
Left	0.3	0.1	0.4	0.25	0.1	0.35	0.1	0.1	0.2	<0.1	<0.1	<0.1
Right	5	3	8	2	3	5	0.6	0.7	1.3	0.2	0.1	0.3
Top	10	0.4	10.4	2.5	0.4	2.9	0.6	0.3	0.9	0.1	<0.1	0.1
Bottom	10	0.7	10.7	5	0.7	5.7	2	0.2	2.2	0.3	<0.1	0.3

contain dose-equivalent rates for bare gauges and in DOT approved transport containers. For each measurement location, measurements are highlighted for the highest neutron dose-equivalent rate and the highest total dose-equivalent. For example, in Table 6-15, "Gauge Alone - Surface," the highest neutron measurement was on the gauge bottom (6.0 mrem/hr), while the highest total dose-equivalent was 27.4 mrem/hr, as measured on the gauge back surface. The latter measurement is important because, in general, at specific distances from a device, the maximum dose-equivalent rate is used for radiation protection purposes. Since many BEE shops do not have neutron instruments, storage and DOT compliance surveys will likely be accomplished through assessment of the  $\gamma$ -radiation field only. Table 6-17 contains a compilation of the fraction of total dose-equivalent measured, if only  $\gamma$ -radiation measurements are collected from the data in Tables 6-15 and -16. The fractions range from 0.60 to 0.98. While the fraction is low for a few cases, in general, most are greater than 0.90. These tables can be used as an aid in appropriately applying  $\gamma$ -only measurements to DOT and storage surveys of Troxler gauges.

TABLE 6-16. Radiation Profile for Troxler Model 3440 Gauge (RRSSD 2001).

Location	Surface			10 cm			30 cm			1 meter		
	$\gamma$	$\eta$	$\gamma+\eta$	$\gamma$	$\eta$	$\gamma+\eta$	$\gamma$	$\eta$	$\gamma+\eta$	$\gamma$	$\eta$	$\gamma+\eta$
Gauge Alone – Dose-Equivalent (mrem/hr)												
Front	19.0	1.5	20.5	5.0	0.5	5.5	1.2	0.2	1.4	0.3	0.1	0.4
Back	18.0	0.8	18.8	6.0	0.4	6.4	1.5	0.2	1.7	0.2	0.1	0.3
Left	13.0	0.4	13.4	3.0	0.2	3.2	0.8	0.1	0.9	0.1	0.1	0.2
Right	12.0	0.6	12.6	6.0	0.3	6.3	3.0	0.2	3.2	0.5	0.15	0.65
Top	19.0	0.9	19.9	3.5	0.6	4.1	0.6	0.4	1.0	0.15	0.1	0.25
Bottom	18.0	1.9	19.9	4.0	1.2	5.2	0.7	0.4	1.1	<0.1	0.1	0.1
Plastic Transport Case – Dose-Equivalent (mrem/hr)												
Front	8.0	0.3	8.3	3.0	0.25	3.25	1.1	0.15	1.25	0.3	<0.1	0.3
Back	7.0	0.3	7.3	3.0	0.2	3.2	1.0	0.1	1.1	0.2	<0.1	0.2
Left	0.4	0.1	0.5	0.3	<0.1	0.3	0.2	<0.1	0.2	0.2	<0.1	0.2
Right	6.0	1.4	7.4	2.0	0.7	2.7	0.6	0.25	0.85	0.2	0.1	0.3
Top	13.0	0.2	13.2	3.0	0.15	3.15	0.9	<0.1	0.9	0.3	<0.1	0.3
Bottom	8.0	0.3	8.3	4.0	0.1	4.1	2.5	0.1	2.6	0.6	<0.1	0.6

TABLE 6-17. Fraction of Total Dose-Equivalent Quantified by  $\gamma$ -Radiation Measurements-Only (From Tables 6-15 and 6-16).

Distance	Surface		10 cm		30 cm		1 meter	
Device	Fraction	Location	Fraction	Location	Fraction	Location	Fraction	Location
3430 Gauge	0.95	Back	0.82	Top	0.91	Right	0.60	Top
3430 (Case)	0.93	Front	0.88	Front	0.91	Bottom	> 0.75	Bottom
3440 Gauge	0.93	Front	0.94	Right	0.94	Right	0.77	Right
3440 (Case)	0.98	Top	0.98	Bottom	0.96	Bottom	> 0.86	Bottom

g. **Detection Efficiency.** The concept of detection efficiency for many instruments is not well understood and often leads to errors in calculated activity or activity concentration. In general, probe detection efficiencies are important for instruments that have response in count rate and integrated counts, like scintillation and G-M detectors.

Radiation emissions from the decay of RAM are random in their spatial orientation. Figure 6-17a illustrates a point source encompassed by a sphere, where the solid angle is  $4\pi$ . If the entire surface of the sphere were sensitive to the radioactive emissions by the point source, this geometrical configuration would have 100 % detection efficiency. Figure 6-17b has the same configuration as Figure 6-17a, except that the RAM is plated on a disc. For this case, 50 % of the particles or photons will be emitted into the upper semi-sphere, while the other 50 % will be emitted into the lower semi-sphere. Ignoring backscatter from the disc, if low-energy  $\beta$  and  $\alpha$ -particles are emitted, they will be absorbed in the disc, with only 50 % of the particles being available for detection. Thus maximum detection efficiency would be 50 %. Figure 6-17c is similar to Figure 6-17b in the disc source, however, the solid angle encompassing the disc is  $2\pi$ , a semi-sphere. Conceptually, this configuration is very similar to many  $\alpha$ -scintillators, like the AP-100 probe on the ADM-300, pancake G-M, and others in that these probes can encompass  $2\pi$  solid angle, if the source is smaller than the entrance window of the detector.

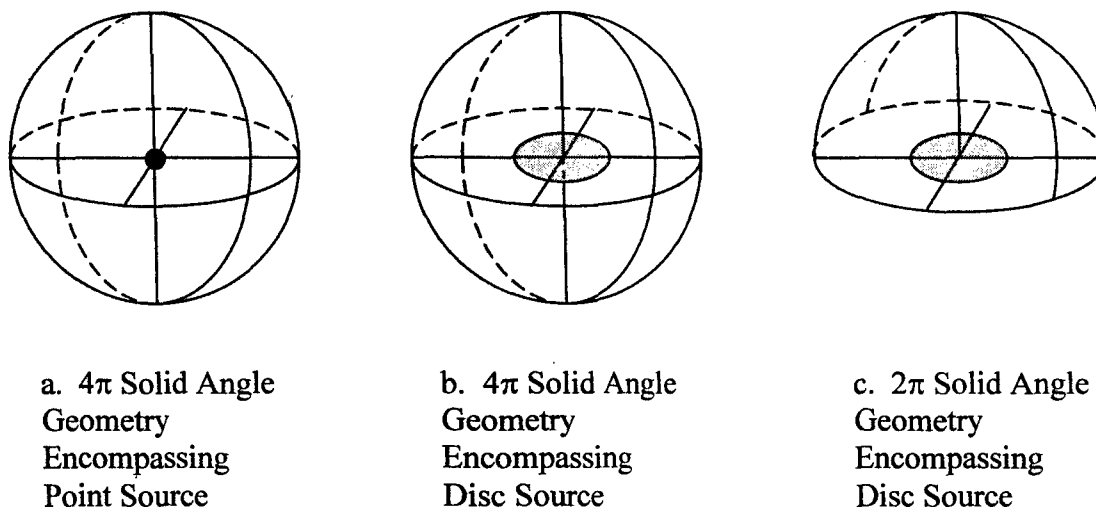


Figure 6-17. Conceptual Model of Detection Geometries.

Many instrument detection efficiencies are reported in terms of a  $2\pi$  detection geometry because many of the sources used to calibrate them are quantified by their  $2\pi$  solid angle radiation emission rate. This is most common to the large-area and small-disc plated sources used to calibrate  $\alpha$ -scintillators,  $\alpha/\beta$ -scintillators, and G-M pancake probes. Unfortunately, most measurement tasks performed with these probes have a requirement to quantify the total activity on a sample (i.e., emissions in a  $4\pi$  solid angle). Therefore, for calculations that relate an instrument's response to

total activity or activity concentration of a sample, detection efficiency must be specified for  $4\pi$  geometry. To convert from a  $2\pi$  to  $4\pi$  detection efficiency, the  $2\pi$  efficiency should be divided by two. Table 6-20 contains a detection efficiency summary for various probe and sample types. Detection efficiencies for most of the  $\gamma$ -scintillation detectors like the FIDLER, 2" x 2", and other NaI(Tl) systems, is dependent on the measurement task. When these systems are used for activity or activity quantification, the units of efficiency are unique to the task and dependent on the source/detector separation distance. The common portable NaI(Tl) systems used in the AF may be used to quantify the activity of point sources and activity concentrations of contaminants on surfaces or volumes (i.e., often surface soils). For these uses, the detection systems are normally specially calibrated for the unique task and radionuclide. As shown in Table 6-20, when portable  $\gamma$ -scintillators are used for RAM search or radionuclide identification, detection efficiencies are normally not required.

h. Thermo-Luminescent Dosimetry. Thermo-luminescent dosimetry (TLD) is primarily used in the AF for personal dosimetry. TLDs are also useful for general area radiation protection measurements. The most common TLDs used in the AF are used for  $\beta$ - and photon radiation dosimetry, while a small fraction are used for neutron dosimetry. Like neutron detectors, neutron TLDs must be used in neutron radiation fields similar to that of calibration. More details on the TLDs available through AFIOH/SDR can be found in AF Manual 48-125.

i. Radiation Detection Instrument Selection for Various AF Measurement Tasks. Table 6-18 contains a summary of recommended instruments for various AF radiation measurement tasks. The table lists instruments in the following categories: optimal, acceptable, and not recommended. While the "not recommended" category is not exhaustive, it does list a number of instruments that BES personnel commonly have inappropriately used for surveys. While a category exists for "optimal," BES should not use this table in justifying the purchase of equipment if BES already possesses an instrument listed in the "acceptable" category for a specified task.

TABLE 6-18. Detection Efficiency Summary for Various Probe and Sample Types Common to BES Tasks.

Probe Type	Sample Being Evaluated	Instrument Response Units	Detection Efficiency Units	Calculated Activity or Activity Concentration (and examples)	Other Considerations
$\alpha$ -scintillators	swipe, filter, or other surface (area <b>smaller</b> than detector entrance window)	count rate (cpm)	unitless ( <b>small</b> source calibration) ( $4\pi$ geometry)	activity (dpm, Bq, $\mu\text{Ci}$ ) or activity concentration ( $\text{dpm}/\text{cm}^2$ , $\text{dpm}/100\text{ cm}^2$ , $\text{dpm}/\text{L}$ , $\text{mCi}/\text{m}^3$ )	1. sample self-absorption, 2. for filters, flow volume must be known
	swipe, filter, or other surface (area <b>larger</b> than detector entrance window)		unitless ( <b>large</b> source calibration) ( $4\pi$ geometry)	activity (dpm, Bq, $\mu\text{Ci}$ ) or activity concentration ( $\text{dpm}/\text{cm}^2$ , $\text{dpm}/100\text{ cm}^2$ , $\text{dpm}/\text{L}$ , $\text{mCi}/\text{m}^3$ )	1. sample self-absorption, 2. for filters, flow volume must be known
$\gamma$ -scintillator	point source	count rate (cpm)	unitless ( $4\pi$ geometry)	activity (dpm, Bq, $\mu\text{Ci}$ )	calibration based on source/detector distance
	surface contamination		activity per area per count rate [ $\text{dpm}/(\text{m}^2 \cdot \text{cpm})$ ] ( $4\pi$ geometry)	activity concentration ( $\text{dpm}/\text{m}^2$ )	1. calibration based on source/detector distance 2. usually infinite plane of contamination assumption
	volumetric contamination encompassing large area		activity per mass or volume per count rate [ $\text{dpm}/(\text{cm}^3 \cdot \text{cpm})$ , $\text{dpm}/(\text{g} \cdot \text{cpm})$ ]	activity concentration ( $\mu\text{Ci}/\text{g}$ , $\text{dpm}/\text{g}$ , $\text{pCi}/\text{cm}^3$ , $\text{Bq}/\text{cm}^3$ )	1. calibration based on source/detector distance 2. usually infinite plane of contamination assumption 3. vertical distribution of contamination assumption
	isotope identification	spectral response	not generally applied	not applicable	energy calibration
	RAM search tasks	relative count rate (cpm)			relative response above background count rates generally used



TABLE 6-19. Radiation Detection Instrument Selection Guide.

Measurement Task	Detectable Radiations		Instrumentation			
	Primary	Secondary	Optimal	Note	Acceptable	Note
General radiation exposure measurements of RAM storage and use areas (no neutron assessment)	$\gamma$ - & x-ray	$\beta$ -particles	Victoreen 451B	1	Victoreen 451P	2
			Victoreen 450 Eberline RO-20 or equivalent	2	Victoreen 450P ADM-300 or equivalent	
General radiation exposure measurements in diagnostic x-ray use areas	x-rays	NA	Victoreen 451B	2	Victoreen 451P	4
			Victoreen 450 Victoreen 470A or equivalent	4	Victoreen 450P ADM-300 or equivalent	5
General radiation exposure measurements in mammography use areas	x-rays	NA	Victoreen 451B	2	Victoreen 451P	4
			Victoreen 450 Victoreen 470A or equivalent	4	Victoreen 450P or equivalent	8
General radiation exposure measurements in NDI operations (primary & scatter)	x-rays	NA	Victoreen 451P	2	Victoreen 451B	2
			Victoreen 450P	9	Victoreen 450 Eberline RO-20 ADM-300 or equivalent	
General radiation exposure measurements from RFR emitters and research x-ray	x-rays	NA	Victoreen 471RF	2	Victoreen 440RF/D	2
			or equivalent	4 10	or equivalent	6 10
DOT dose-equivalent rate compliance measurements (neutron component, ie. Troxler Gauge)	$\gamma$ - & x-ray	neutron	ADM-300 NP-100 or equivalent	12	Calculation	12 13
					Instruments Not Designed for Neutrons	
General radiation exposure measurements of RAM storage and use areas (no neutron assessment)	$\gamma$ - & x-ray	$\beta$ -particles	Victoreen 451B	1	Victoreen 451P	2
			Victoreen 450 Eberline RO-20 or equivalent	2	Victoreen 450P ADM-300 or equivalent	
General radiation exposure measurements in diagnostic x-ray use areas	x-rays	NA	Victoreen 451B	2	Victoreen 451P	4
			Victoreen 450 Victoreen 470A or equivalent	4	Victoreen 450P ADM-300 or equivalent	5
General radiation exposure measurements in mammography use areas	x-rays	NA	Victoreen 451B	2	Victoreen 451P	4
			Victoreen 450 Victoreen 470A or equivalent	4	Victoreen 450P or equivalent	8
General radiation exposure measurements in NDI operations (primary & scatter)	x-rays	NA	Victoreen 451P	2	Victoreen 451B	2
			Victoreen 450P	9	Victoreen 450 Eberline RO-20 ADM-300 or equivalent	
General radiation exposure measurements from RFR emitters and research x-ray	x-rays	NA	Victoreen 471RF	2	Victoreen 440RF/D	2
			or equivalent	4 10	or equivalent	6 10
DOT dose-equivalent rate compliance measurements (neutron component, ie. Troxler Gauge)	$\gamma$ - & x-ray	neutron	ADM-300 NP-100 or equivalent	12	Calculation	12 13
					Instruments Not Designed for Neutrons	

TABLE 6-19. Radiation Detection Instrument Selection Guide (continued).

Measurement Task	Detectable Radiations		Instrumentation			
	Primary	Secondary	Optimal	Note	Acceptable	Note
DOT dose-equivalent rate compliance measurements (no neutron assessment)	$\gamma$ - & x-ray	NA	Victoreen 451B, 450P, 451P, 450 Eberline RO-20 ADM-300 or equivalent	2	Victoreen 471RF	5
					Victoreen 440RF/D	3
					ADM-300 XP-100	7
DOT removable, other removable samples, and air filter $\alpha$ -contamination assessment	$\alpha$	Potential $\beta$ , $\gamma$ , x-ray	Ludlum 43-89 or equivalent	14 17	ADM-300 AP-100 Ludlum 43-90 or equivalent	15 16 18
DOT removable, other removable samples, and air filter $\beta$ -contamination assessment	$\beta$	Potential $\alpha$ , $\gamma$ , x-ray	Ludlum 43-89 or equivalent	14	ADM-300 BP-100	19
				17	Pancake G-M	16 18 20
Pre-screening sealed source leak tests for $\alpha$ -contamination	$\alpha$	Potential $\beta$ , $\gamma$ , x-ray	Ludlum 43-89 or equivalent	14 17	Ludlum 43-90 ADM-300 AP-100 or equivalent	15 16 18
Pre-screening sealed source leak tests for $\beta$ -contamination	$\beta$	Potential $\alpha$ , $\gamma$ , x-ray	Ludlum 43-89 or equivalent	14	ADM-300 BP-100	19
				17	Pancake G-M	16 18 20
Assessment of total [fixed & removable] $\alpha$ -contamination on surface	$\alpha$	Potential $\beta$ , $\gamma$ , x-ray	Ludlum 43-89 or equivalent	14 17	Ludlum 43-90 ADM-300 AP-100 or equivalent	15 16 18

TABLE 6-19. Radiation Detection Instrument Selection Guide (continued).

Measurement Task	Detectable Radiations		Instrumentation					
	Primary	Secondary	Optimal	Note	Acceptable	Note	Not Recommended	Note
Assessment of total [fixed & removable] $\beta$ -contamination on surface	$\beta$	Potential $\alpha$ , $\gamma$ , x-ray	Ludlum 43-89 or equivalent	14	ADM-300 BP-100	18	Victoreen 450 & 451B Eberline RO-20	19
				17	Pancake G-M	16 18		20
Screening areas for photon-emitting RAM or searching for a lost source	$\gamma$ - & x-ray	Potential $\alpha$ & $\beta$	Ludlum 19 SPA-3 NaI(Tl) or equivalent		Pancake G-M Victoreen 451B, 450P, 451P, 450 Eberline RO-20 or equivalent		ADM-300 AP-100 Ludlum 43-89, -90 or equivalent	17
Screening aircraft interiors for $^{226}\text{Ra}$ parts	$\beta$ , $\gamma$ , x-ray	Maybe $\alpha$ (but, only if leaking)	Pancake G-M ADM-300 BP-100 ADM-300 XP-100 or equivalent		Ludlum 19 Victoreen 451B, 450P, 451P, 450 Eberline RO-20 or equivalent		ADM-300 AP-100 Ludlum 43-89, -90 or equivalent	17
Screening soil and other surfaces for DU, $^{226}\text{Ra}$ , & MagThor contamination	$\alpha$ , $\beta$ , $\gamma$ , x-ray	NA	Pancake G-M ADM-300 BP-100 ADM-300 XP-100 or equivalent		ADM-300 AP-100 Ludlum 43-90	21	Ludlum 19 Victoreen 451B, 450P, 451P, 450 Eberline RO-20 or equivalent	20
					Ludlum 43-89 SPA-3 NaI(Tl)	17		
					ADM-300 XP-100	20		

TABLE 6-19. Radiation Detection Instrument Selection Guide (continued).

Measurement Task	Detectable Radiations		Instrumentation			
	Primary	Secondary	Optimal	Acceptable	Not Recommended	Note
Screening soil for buried (i.e., > 1 cm) DU, $^{226}\text{Ra}$ , MagThor, and other photon-emitting RAM	$\gamma$ - & x-ray	NA	SPA-3 NaI(Tl) or equivalent	ADM-300 XP-100 FIDLER NaI(Tl) or equivalent	ADM-300 Pancake G-M Ludlum 19 Victoreen 451B, 450P, 451P, 450 Eberline RO-20 or equivalent	20
Screening areas for pure $\beta$ -emitting RAM or searching for a lost source (see Table 3-5)	$\beta$	Potential x-rays $\beta$ -strahlung	Pancake G-M	Victoreen 450, 451B Eberline RO-20 ADM-300	ADM-300 XP-100 Victoreen 450P, 451P	22
			ADM-300 BP-100 or equivalent	Ludlum 43-89	Ludlum 19 SPA-3 NaI(Tl)	23

## Notes:

1. Instruments with a  $\beta$ -particle window offer an opportunity to differentiate  $\beta$ - and photon-radiations.
2. Uniformity of energy response.
3. Non-uniform energy response.
4. Integrate mode allows measurement of pulsed fields.
5. Slightly degraded response to low-energy photons.
6. Instrument has rate mode only.
7. Instrument not designed to measure this type of radiation field.
8. Moderately degraded response to low-energy photons.
9. Pressurized ion chambers generally more sensitive to low intensity fields.
10. Designed to minimize RFR interference.
11. Subject to RFR interference.
12. Requires photon radiation assessment as well.
13. Use manufacturer's radiation profiles as assistance with photon measurements if neutron equipment is not available.
14. Discriminates  $\alpha$ - and  $\beta$ -radiations.
15. Very low-sensitivity to  $\beta$ - and photon radiations.
16. Inability to differentiate  $\alpha$ -,  $\beta$ -, and photon interactions.
17. Insensitive to photon radiations.
18. Inability to differentiate  $\beta$ - and photon interactions.
19. Surface attenuation will degrade  $\alpha$ -particle detection.
20. High background radiation level.
21. No  $\beta$ -particle sensitivity.
22. Sensitive to only high energy  $\beta$ -particles.
- 23.

## 7. Surveys in Support of Radiation Protection Program.

a. General. Surveys are one of the most important activities conducted by BES. While some view the term to be limited to measurement tasks, this report shall use the term more broadly to encompass "reviews" that may include measurements, evaluation of personal protective equipment, facility layout review, evaluation of RAM packages prior and during opening, etc. While this report has an emphasis on measurements, other survey activities will be reviewed as they are important to radiation protection programs.

b. General Public Surveys. Evaluation of radiation exposure to members of the general public is required for a number of AF RAM and machine-generated radiation environments. AFI 48-148 defines the primary annual dose-equivalent level for members of the general public (Table 5-1 of this report) at 100 mrem in a year. For NRC-licensed RAM used under the AF's Master Materials License annual demonstration of adherence to the limit must be made and documented. Other limits may be applicable and are discussed in more detail later in this section. Compliance with exposure limits can be met by many methods or a combination of methods, dependent on the activity and use area involved. Methods commonly used are survey measurements, calculations, manufacturer's specifications, and health physics evaluation of radiation sources.

Table 7-1 lists general public surveys for a variety of AF radiation use areas. In the case of nuclear medicine, four separate areas are considered for public dose assessment. For unrestricted areas in the vicinity of the Department, like offices, corridors, and patient/visitor waiting areas, annual dose assessments are required. These assessments are commonly accomplished by portable survey instrument measurements in combination with calculations to estimate annual exposure. In some cases, TLD studies may be effective in demonstrating compliance. For nuclear medicine departments that administer therapeutic dose of radioiodine to in-patients, special surveys must be accomplished for the room during the in-patient stay and on residual contamination once the patient has been discharged, if it is desirable for the room to be occupied by another patient.

For some sealed source RAM, there is little to no potential for external exposure because radiations emitted are completely absorbed within the source or instrument housing. Good examples of this are self-illuminating exit signs that possess  $^3\text{H}$ , ionscans and chemical agent monitors that contain  $^{63}\text{Ni}$ , and devices that contain  $^{187}\text{Re}$  and  $^{210}\text{Po}$ . For these examples, a measurement survey to demonstrate compliance would be futile. For these cases, it is recommended that the lack of external radiation emissions and subsequent compliance with the standard be documented.

While some of the use areas listed in Table 7-1 may require less periodic surveys to demonstrate overall compliance with the annual limit, it must be accomplished at least annually for NRC-regulated RAM. While some use areas may have initial surveys that include measurements, annual updates may not require additional survey measurements. An annual update for storage areas where there are not any changes that would affect public exposures (i.e., isotopes being stored, quantity, and location), case files may have a simple acknowledgement that current conditions are the same as the initial survey. This is commonly done for storage areas that contain lead-base paint analyzers,  $^{241}\text{Am}$ -containing chemical agent detectors, and other small sources. For some radiation exposure scenarios, general public and occupational exposure may be accomplished by the same survey.

TABLE 7-1. Typical General Public Exposure Surveys for Various AF Radiation Use Areas.

AF Activity	Use Area	External Radiation	Potential Internal Exposure
Nuclear Medicine	Patient/Visitor Waiting Areas Offices/Corridors Around Department	Yes	Minimal
	In-Patient Radioiodine Therapy	Yes	Yes
	Hot Lab	Yes	Radioiodines & Others Exhausted
	Patient Imaging & Dosing Areas	Yes	Spills & Typical Contamination
Medical/Dental X-Ray	Patient/Visitor Waiting Areas Offices/Corridors Around Department	Yes	No
Sealed RAM Sources	Vicinity of Storage & Use Areas	Yes	Unlikely, Only if Leaking Source
DU & MagThor Operations	Vicinity of Storage & Use Areas	Yes	Minimal, Contamination Localized in Occupational Areas
Laboratory	Vicinity of Storage & Use Areas for Sealed and Unsealed RAM	Yes	Exhaust & Surface Contamination
Industrial X-Ray NDI	Vicinity of Parts Examination Area	Yes	No
Research X- Ray/Accelerator	Vicinity of Research Laboratories	Yes	Minimal, Only for High Energies
Baggage X-Ray, Lead-Based Paint X-Ray Machines	Examination Areas (Offices, AMC Terminals, etc.)	Yes	No

Table 7-2 lists the general public exposure limits followed in the AF, based on 10 CFR 20. The first two categories will be commonly applied by BES. The other categories are less common to AF operations, since most AF operations do not have significant potential for internal exposure to members of the public, and those that involve unsealed RAM are in controlled areas. Of the areas that use unsealed RAM, nuclear medicine is the most common in the AF and have a designated RSO in the department. These use areas are normally surveyed by nuclear medicine technicians with assistance from BES, more notably in evaluation of radioiodines and noble gas exhausts.

c. Occupational Surveys.

(1) Radiation Exposure. For the AF activities listed in Table 7-1, there is a comparable listing in Table 7-3 that is applicable to occupational exposures. In general, the exposures are the same, except for magnitude of exposure. For example, while members of the general public in the

TABLE 7-2. General Public Exposure Limits (10 CFR 20).

Category	Limit	Reference
External & Internal	100 mrem in a year	Part 20.1301(1)
Unrestricted Areas (External)	2 mrem in any one hour	Part 20.1302(2)
Internal (Gases, Suspended Liquids & Solid, etc.)	Isotope-Specific Concentration Limits (meet 100 mrem in a year)	Table 2, Appendix B Part 20
Surface Contamination (Removable & Total)	Recommended Surface Concentration Limits (meeting 100 mrem in a year)	Reg. Guide 1.86
Air Emissions to the Environment	10 mrem in a year, excluding Rn-222 and its daughters	Part 20.1101(d)

TABLE 7-3. Typical Occupational Exposure Surveys for Various AF Radiation Use Areas.

AF Activity	Use Area	External Radiation	Potential Internal Exposure
Nuclear Medicine	RAM Storage	Yes	Minimal
	Radioiodine Therapy	Yes	Yes
	Hot Lab	Yes	Radioiodines & Others Exhausted
	Patient Imaging & Dosing Areas	Yes	Spills & Typical Contamination
Medical/Dental X-Ray	X-Ray Suites/Corridors In Department	Yes	No
Sealed RAM Sources	Vicinity of Storage & Use Areas	Yes	Unlikely, Only if Leaking Source
DU & MagThor Operations	Storage & Use Areas	Yes	Moderate, Contamination Localized in Work Areas
Laboratory	Storage & Use Areas for Sealed & Unsealed RAM	Yes	Surface Contamination
Industrial X-Ray NDI	Aircraft Examination Area	Yes	No
Research X-Ray/Accelerator	Research Laboratories	Yes	Minimal, Only for High Energies
Baggage X-Ray, Lead-Based Paint X-Ray Machines	Examination Areas (Offices, AMC Terminals, etc.)	Yes	No

vicinity of medical x-ray suites are exposed to low levels of external x-radiation, exposure to medical x-rays technologists and physicians is generally higher. Specifically, for nuclear medicine technicians and physicians, potential for internal exposure may be assessed by measurements (in-situ

bioassay, urine assays, contamination surveys, and others) or calculations for routine radioiodine exposures and for exposures from radionuclide spills. These, in general, will not be performed for the general public, except for in-patient radioiodine therapy room clearance.

(2) Individual Monitoring. While survey measurements, calculations, and TLD area-studies may be used to assess occupational exposure, individual monitoring accomplished by TLDs, electronic dosimeters, or passive dosimeters are commonly employed for AF workers with the potential for higher exposures. Individual monitoring for AF radiation workers is required if the individual has a potential for exposure in excess of 10 % of the respective limit for all categories except TEDE for minors, which is 100 mrem in a year, and deep dose equivalent to declared pregnant females (protection of the embryo/fetus), which is 100 mrem. AFM 48-125 provides more detail on individual monitoring.

(3) Personal Protective Equipment. Evaluation of the condition of personal protective equipment and/or a protective equipment program should be accomplished by BEEs as required. Some important examples are discussed. AFI 48-148 (para. 4.4.11) requires that leaded aprons, gloves, and syringe shields be stored correctly and inspected annually for defects like holes, cracks, and tears. While this is a primary responsibility for a unit RSO, BES, as installation RSOs, have an overall responsibility to evaluate radiation safety effectiveness (AFI 48-148, para. 2.15.1). While the use of respiratory protection is rare for routine AF RAM operations, the respiratory protection program could have applicability to individuals working with RAM in accident/deployment scenarios, where the Nuclear Accident Response Procedures (NARP) is applicable to nuclear weapons accidents. The provisions of the existing AF respiratory protection program are adequate for exposures to RAM.

(4) Engineering Controls. Engineering controls typically include portable and structural shielding, ventilation systems like hoods in laboratories and vented boxes common to nuclear medicine hot labs, interlocks, alarms, and others used to limit radiation exposures. All of these controls should be evaluated by BES at least annually during shop visits, with the exception of ventilation systems which may be on a more frequent schedule.

d. Radiation Protection for Medical Use of Radiation. AFI 48-148, Chapter 4 provides extensive details on radiation protection for medical practices. While most of requirements listed in Chapter 4 are the primary responsibility of other organizations in the medical treatment facility (MTF), as noted above, BES, as installation RSOs, have an overall responsibility to evaluate radiation safety effectiveness (AFI 48-148, para. 2.15.1). Quality control and entrance skin exposure guidance (ESEG) are key requirements under Chapter 4 that BES should direct more attention, since issues in this program require a fair amount of technical competence. Among the requirements of Chapter 4, BES at a minimum should:

(1) periodically review the quality control program for diagnostic imaging departments,

(2) assess the adequacy of acceptance testing for new diagnostic imaging systems, system that have undergone significant component change, and nuclear medicine gamma cameras,



(3) review annual compliance inspections on diagnostic imaging systems accomplished by medical equipment repair center (MERC) or biomedical equipment technician (BMET),

(4) annually estimate entrance skin exposure (ESE) for common diagnostic procedures on stationary radiography equipment, based on measurements collected by MERC or BMET, unless a health or medical physicist accomplishes this function. AFIOH published AL/OE-TR-1997-0162 to provide specific details on ESE and its measurement.

e. Administrative Controls. Administrative controls generally consist of caution and warning signs, RAM caution labels, locks, training, hours of operation, operating instructions (OIs), exposure restrictions (for example non destructive inspection procedures at night), and other controls that restrict access from members of the general public or non-radiation workers. BES should review these controls for adequacy during routine shop visits.

f. NRC-Licensed RAM. For NRC-licensed RAM use under an AF permit, annual program audits are required. Review of public and occupational exposures, engineering and administrative controls should be a part of an annual permit review.

g. Recommended Survey Frequency. Radiation exposure areas in AF operations should be surveyed at least annually. As noted earlier in this section, measurements are not always a part of annual surveys if the initial survey is adequate or if measurements are not meaningful to the evaluation. Scheduling more frequent survey is primarily based on professional judgment that considers:

- (1) potential for temporal changes in the radiation exposure magnitude,
- (2) potential risk for exposures over a limit, and
- (3) potential for internal exposure from unsealed RAM.

Table 7-4 provides a listing of recommended survey frequencies for various AF activities, based on these criteria. BES, based on professional judgment of their operations, may have different survey frequencies.

TABLE 7-4. Recommended Survey Frequency for AF Work Locations with Radiation Exposure Potential.

AF Activity	Use Area	Recommended Frequency*
Nuclear Medicine	RAM Storage	Quarterly (more frequently if significant temporal changes in RAM quantities occur)
	Radioiodine Therapy (In-Patient)	At least once at time of patient placement and post patient discharge
	External Radiation for Patient Imaging & Dosing Areas	At least annually (more frequently if significant changes occur in patient workload and/or RAM quantities)
	Contamination in Patient Imaging & Dosing Areas	Daily frisking surveys in used areas.
Medical/Dental X-Ray	X-Ray Suites/Corridors in Department	At least annually or after addition of new radiation-producing machine
Sealed RAM Source	Storage & Use Areas	Annually (more frequently if significant temporal changes in RAM quantities occur)
DU Storage	Storage & Handling	Annually (more frequently if significant temporal changes in RAM quantities occur)
DU & MagThor Operations	External Radiation for Storage & Use Areas	Quarterly (more frequently if significant temporal changes in RAM quantities occur)
	Contamination in Storage & Use Areas	Daily frisking surveys in used areas. Quarterly removable wipe analysis.
Laboratory	External Radiation for Sealed & Unsealed RAM	Quarterly (more frequently if significant temporal changes in RAM quantities occur)
	Contamination in Storage & Use Areas	Daily frisking surveys in used areas. Quarterly removable wipe analysis.
Industrial X-Ray NDI	Shielded (Permanent) Aircraft Examination Area	At least annually or after addition of new radiation-producing machine
	Unshielded (Temporary) Aircraft Examination Area	At the time of any new x-ray configuration
Research X-Ray/Accelerator	Research Laboratories	At least annually or after addition of new radiation-producing machine
Baggage X-Ray, Lead-Based Paint X-Ray Machines	Examination Areas	At least bi-annually or after addition of new radiation-producing machine

\* Some surveys may be mandated by AF permit conditions

## 8. Dosimetry Review.

a. General. AFM 48-125, "Personnel Ionizing Radiation Dosimetry" was planned for publication during preparation of this report. AFM 48-125 provides extensive detail on running a dosimetry program. This report highlights issues that have been problematic from a BES standpoint.

b. BES Dosimetry Review. One of the most important duties of BES with respect to radiation dosimetry results that are reported on the Listing 1499-1 (for TLD monitoring period) and the 1499-2 (annual report) is reviewing the data for compliance with occupational exposure limits from Table 5-1 of this report, evaluating them with respect to investigation action levels (IALs), and determining if the RSO needs to investigate the exposure to an individual because a dosimeter was lost, damaged, etc. and an administrative dose has been applied to the record.

(1) Occupational Exposure Limits. Table 8-1 provides a summary of Listing 1499 categories of exposure reporting, exposure limit categories, annual occupational limits, and administrative-scaled limits for quarterly and monthly periods. It is important to note that 10 CFR 20 does not have quarterly or monthly limits for most personnel monitored, and the scaled limits are for administrative purposes only. The only exception to this rule is for the embryo/fetus, where the combined deep dose equivalent and committed dose equivalent is applicable to the remainder of a declared pregnancy, and efforts shall be made to "avoid substantial variation above a uniform monthly exposure rate" to ensure compliance [10 CFR 20.1208(b)]. The Listing 1499 contains eight reporting categories as listed in Table 8-1. For each category, there is also an exposure limit

TABLE 8-1. Radiation Exposure Limits (10 CFR 20) for Various Individual Monitoring Categories (Embryo/Fetus & Minors not Included).

AF Center for Radiation Dosimetry Listing 1499 Category	10 CFR 20 Exposure Limit Category	Annual Occupational Limit (rem)	Scaled Limits Administrative (rem)	
			Quarterly	Monthly
Eye Dose Equivalent	Lens of Eye	15	3.75	1.25
Extremity Dose Equivalent	Extremities	50	12.5	4.17
Shallow Dose Equivalent	Shallow Dose Equivalent	50	12.5	4.17
Head Dose Equivalent (Deep)	Deep Dose Equivalent & Committed Dose Equivalent  (to individual organ or tissue, except lens)	50	12.5	4.17
Deep Dose Equivalent (B/G/X)				
Deep Dose Equivalent (NEUT)				
Committed Dose Equivalent (CDE)				
All Sources Total Effective Dose Equivalent (TEDE)	Total Effective Dose Equivalent (TEDE)	5	1.25	0.417

category, based on 10 CFR 20. It is important to note that while there are eight dosimetry reporting categories, there are only three annual limit levels: 5, 15, and 50 rem. Reported dose-equivalent levels must be less than the respective annual limit for compliance. For review of quarterly or monthly dosimetry results, it is customary to use scaled limits in review of dosimetry results. However, it is important to note, that occupational exposure limits scaled to time period less than a year have no regulatory basis. As such, if a scaled limit is exceeded, it is important for an RSO to have concern that an operation involving radiation exposure may require modification to reduce personnel exposures, but reporting the exposure as an “overexposure” is not warranted unless an annual limit has been exceeded.

(2) Investigation Action Levels. Proper assignment of and review of dosimetry with respect to IALs is an important part of an effective as low as is reasonably achievable (ALARA) program. AFM 48-125 defines IALs as, “A dose equivalent value or radionuclide intake activity set by the installation RSO that requires further investigation when exceeded. Levels are normally tailored to each using section’s historical dosimetry data in order to promptly identify and correct adverse trends.” In general, IALs should be developed for each dose-equivalent category on the Listing 1499 for individual reporting periods and the annual report. The following guidance is provided in setting IALs.

(a) IALs should not be set at the annual limit or a scaled one based on the annual limit. Setting an IAL to the limit in principal is not in the spirit of achieving ALARA and is not an effective tool.

(b) Setting IALs for total effective dose equivalent less than 100 mrem in a year (or at a scaled fraction of this for quarterly or monthly dosimetry reviews) is inappropriate since these levels are less than the limit to the general public. If occupational exposures are consistently below general public limits, there is not a need for individual monitoring, unless there is a possibility of exposures in excess of 10% of the annual limit.

(c) In general, setting an IAL for eye and head dose equivalents for most occupationally exposed AF employees is not useful. A noted exception is for personnel working in medical x-ray that are assigned collar dosimeters and wear lead aprons to reduce dose to the body. Physicians using fluoroscopic x-ray have the highest potential for exposures of this type.

(d) In general, setting IALs for extremity and skin exposures for most occupationally exposed AF employees is not useful unless the employee has been assigned an extremity dosimeter (i.e. finger badge). The most common AF employees using extremity dosimeters are: nuclear medicine technicians, physicians using fluoroscopic x-ray, DU maintenance operators (i.e. counterweight repair), and some laboratory research employees using  $\beta$ -particle emitting tracers. For these employees, extremity IALs may be more important than that for total effective dose equivalent.

(e) Since most AF employees do not work with unsealed RAM, and those that do generally have very low anticipated internal uptake, committed dose equivalent dosimetry reports will be rare. As such, assignment of IALs for committed dose equivalent will not generally be necessary.

Table 8-2 contains recommended IAL ranges for radiation dosimetry reviews, that are based on 10 to 25 % of the annual limits. IALs for individual work areas should be specifically tailored to the operation, with Table 8-2 as a guide.

TABLE 8-2. Recommended Investigation Action Level  
Ranges for Radiation Dosimetry ALARA Reviews.

Exposure Limit Category	Dosimetry Period (rem)		
	Annual	Quarterly	Monthly
Total Effective Dose Equivalent	0.5 – 1.25	0.13 – 0.31	0.042 – 0.10
Lens of Eye	1.5 – 3.75	0.37 – 0.94	0.13 – 0.31
Extremity, Shallow, Deep Dose, Committed Equivalent, and Head Dose Equivalent	5 – 12.5	1.3 – 3.1	0.42 – 1.0

c. Categories of Employees & General Public Based on Exposure Potential. Table 8-3 summarizes dosimetry and training requirements for workers and the general public based on exposure category. For the first category, where exposure potential is less than two (2) mrem in any one hour and 100 mrem in a year, there aren't any dosimetry or training requirements for workers – workers are treated like members of the general public for these exposures. For exposures greater than these, but less than 10 % of the annual occupational exposure limit, dosimetry surveillance is not required for workers, but worker radiation safety training is required. For some AF workers that have access to devices like CAMS, ICAMS, small check sources, etc., neither dosimetry or radiation safety training is required because exposures are not anticipated to exceed general public limits.

TABLE 8-3. Dosimetry Surveillance and Training Requirements for AF Workers and Members of the General Public Based on Radiation Exposure Potential.

Exposure Potential (Whole Body)	Instruction to Workers (Training)		Dosimetry Surveillance (TLDs, etc.)	
	Workers	General Public	Workers	General Public
< 2 mrem in any one hour and < 100 mrem in a year	None Required	None Required	None Required	None Required
> 2 mrem/hr or > 100 mrem in a year, but < 500 mrem in a year	Yes	Not Applicable	None Required	Not Applicable
> 500 mrem in a year	Yes		Yes	

## 9. Leak Test Pre-Screen, Wipe Sample, Air Filter, and Surface Contamination Analysis.

a. **General.** Field analysis of air filters, wipe samples to assess removable contamination, and leak tests are commonly accomplished by BES with portable radiation detection instruments. Table 9-1 contains a summary of general analysis requirements for these samples. As noted in the table, regulatory compliance measurements with portable instruments are recommended only for DOT removable contamination assessments, while the other categories recommend laboratory analysis. Pre-screening with portable instruments is recommended for all samples that will receive subsequent

TABLE 9-1. General Analysis Requirements for Contamination on Filters and Wipes.

Method	Air Filter Radiological Assessment	Removable Contamination from Surface Assessment	DOT Removable Contamination Assessment	Sealed Source Leak Test
Recommended Analysis Method for Regulatory Compliance	Laboratory	Laboratory	Portable Instrument	Laboratory <sup>1</sup>
Portable Instrument				
Pre-screening	Recommend	Recommend		Recommend
Instrument Calibration	Required	Required	Required	Recommend
Regulatory Compliance	Sometimes <sup>3</sup>	Sometimes <sup>3</sup>	Yes	Sometimes <sup>2</sup>
Laboratory Analysis				
Comment	NIST Traceable	NIST Traceable	Generally, not performed	NIST Traceable

Notes:

1. Most AF permits require NIST-traceable analysis by AFIOH/SDR or another NRC-approved laboratory.
2. For In-flight Blade Inspection System (IBIS) sources in deployed scenarios, analysis of leak tests by the aircraft-mounted G-M is acceptable.
3. If approved in a work-plan for a remediation, or in a permit for routine surveillance.

laboratory analysis. Most BES will perform the measurements with ADM-300 and associated probes, while some organizations will possess other instruments like the Ludlum 43-89 probe with associated meter. Regardless of the portable instrument being used, the probe/meter combination must be calibrated to the type of radiation being measured, if the measurement is being used for compliance. For example,  $\alpha$ -radiation probes should be calibrated to an  $\alpha$ -radiation emitting source like  $^{239}\text{Pu}$ ,  $^{230}\text{Th}$ , etc. And  $\beta$ -radiation probes, like pancake G-Ms or  $\alpha/\beta$ -scintillators, should be calibrated to  $\beta$ -radiation emitting sources like  $^{99}\text{Tc}$ ,  $^{90}\text{Sr}/^{90}\text{Y}$ , etc. It is important to note that many G-M pancake probes are calibrated only to  $\gamma$ -radiation from sources like  $^{137}\text{Cs}$ , and this is unacceptable for compliance measurements.

b. Measurement Methodology.

(1) **Sample Collection.** Sample collection should be accomplished according to specific guidance provided for the type of sample. Table B-1, Appendix B provides a procedural checklist for collection of sealed source leak test samples. Section 10 provides details on DOT package shipment preparation. Nuclear Weapon Accident Response Procedures (NARP), DoD 3150.8-M (DoD 2005) provides guideline on collection of air samples for nuclear weapons accidents and other types of radiological incidents and accidents.

(2) **Measurement.** The ADM-300 and other instruments have the option of collecting the measurement in "rate" or "scaler" (integrate) modes, while some instruments only measure in the rate mode. Due to fluctuations in meter response while in rate mode, it is easier to make quantitative measurements in the scalar mode. When collecting measurements, the probe entrance window should be in close vicinity of the sample without touching it.

(a) **Battery and Check Source Response Confirmation.** Prior to collecting measurements, perform a battery check on the instrument and verify proper instrument response with a check source appropriate to the probe. Some instruments, like the ADM-300, have automatic battery checks.

(b) **Background Measurement.** A background measurement should be collected prior to measurement of the sample. For leak tests, measure the swipe paper prior to swiping the source. For other samples, it may be appropriate to collect a background measurement on a sample filter/paper.

(c) **Scaler (Integrate) Mode with ADM-300.** To operate in scaler mode with the BP-100 or AP-100 probe connected, depress the **MODE** switch until the display indicates "To enter Scaler, Push SET". Depress **SET** to continue. The default integration period for scaler mode is one (1) minute, which is recommended for most measurements of this type. If other integration periods are desired, depress the  $\uparrow$  switch to set a different time. When in scaler mode, depress the **SET** switch to initiate an accumulation. During accumulation, the display will show accumulated counts and time remaining on the integration period. At the end of the accumulation period, the integrated counts will be displayed. Remember, that when changing from one external probe to another, the instrument must be turned off, and not turned on until the second probe has been connected.

(3) **Detection Efficiency.** The detection efficiency for a probe/measurement system is needed to determine the amount of radioactivity on the sample. For  $\alpha$ -radiation detectors, the efficiency is based on measurement with a plated National Institute for Standards and Technology (NIST) traceable source. As discussed in para. 6d(3)(a), the detection efficiency of an  $\alpha$ -particle emitter retained on a filter paper is significantly lower than that for plated calibration sources that are typically used for calibrations. A correction factor of 40 % is recommended to account for differences in efficiency.  $\beta$ -particles detection efficiency discrepancies between plated calibration sources and those retained on filter papers are not as significant as that of  $\alpha$ -particles, unless it is a low-energy  $\beta$ -particle emission spectrum, like that from  $^{14}\text{C}$ . Pancake G-Ms and  $\alpha/\beta$ -scintillators are normally only calibrated to one  $\beta$ -particle source that should be listed on the instrument's calibration label and certificate. Since the  $\beta$ -particle detection efficiency can have significant variability dependent on the energy spectrum of the isotope being measured, conservative corrections should be

made by users if the measured isotope is different than that of calibration. Table 9-1 contains a  $\beta$ -particle detection efficiency plot for various  $\beta$ -particle emitters based on maximum spectral energy. This plot can be used as an aid in making  $\beta$ -particle emission corrections.

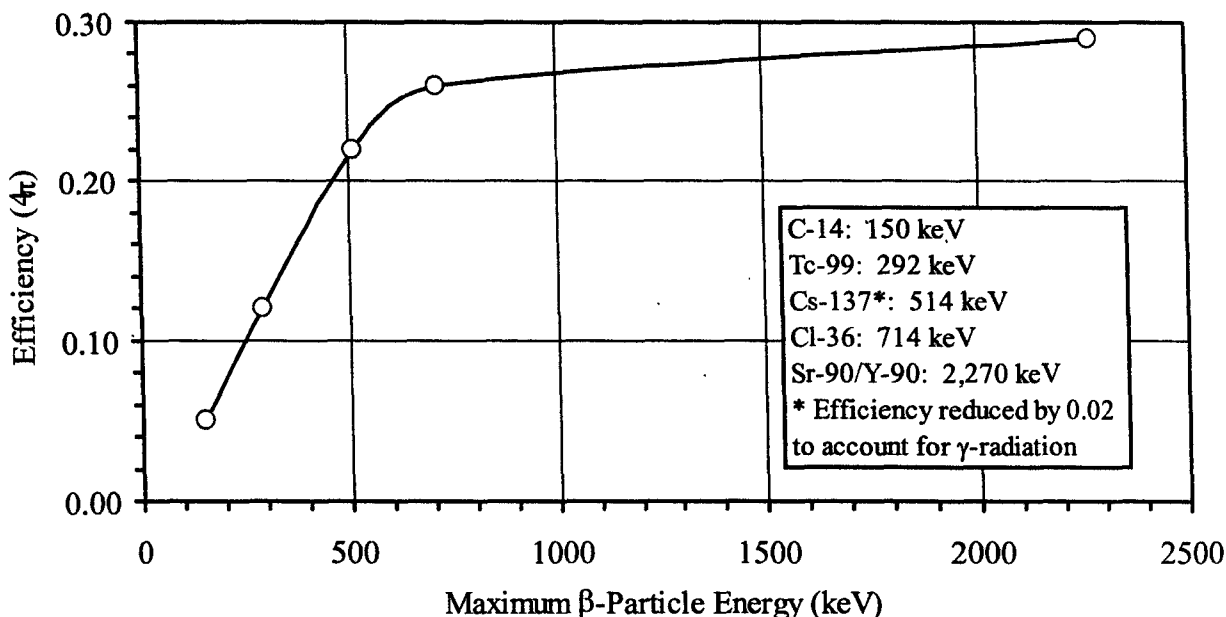


Figure 9-1. Detection Efficiency of Victoreen Model 489-110 Pancake G-M from Table 6-10.

(4) Example  $\beta$ -Particle Detection Efficiency Correction. Assume that you need to perform a measurement on a swipe sample that potentially contains  $^{147}\text{Pm}$ , a pure  $\beta$ -particle emitter with maximum spectral energy of 224 keV (see Table 3-5). You are using the pancake G-M, with detection efficiencies illustrated in Figure 9-1, that is calibrated to  $^{99}\text{Tc}$ , having an efficiency of 0.12 ( $4\pi$ ). From a paper and pencil interpolation of Figure 9-1, the efficiency for  $^{147}\text{Pm}$  is about 0.085. It is reasonable to scale the efficiencies of Figure 9-1 to other pancake G-M probes that have similar  $\beta$ -window area and density thickness, like the Bicron PGM and Ludlum 44-9. Since the ADM-300, has a  $\beta$ -window density thickness much greater than the former three, Figure B-1 should be used.

#### c. Examples.

(1) DOT Non-Fixed (Removable) Contamination Assessment. As described in Section 5e, all packages containing RAM that are offered for transport and the receipt of packages labeled with "Radioactive White I, Yellow II, or Yellow III" require contamination surveys to assess compliance with DOT acceptable removable contamination limits. In this example, it is assumed that a package offered for transport contains  $^{241}\text{Am}$ . Since  $^{241}\text{Am}$  is an  $\alpha$ -particle emitter, it is appropriate to collect  $\alpha$ -radiation measurements. Table 9-2 contains a summary of data regarding the measurements. The first step is calculation of detection efficiency for the measurement. Table 9-2 lists an efficiency of 0.18 ( $^{239}\text{Pu}$ ). Since the calibration was based on a plated source and the measured source is retained on paper, a correction factor of 0.4 is applied, making the corrected efficiency **0.072**. For packages that are used for repeated RAM shipments,  $\alpha$ - and  $\beta$ -assessments should be made.



TABLE 9-2. Data for  $^{241}\text{Am}$  Example DOT Shipment.

Measurement Instrument	ADM-300 w/ AP-100 Probe	Detection Efficiency (Certificate)	$^{239}\text{Pu}$ : 0.18 (4 $\pi$ )
Background Measurement	2 counts (1 minute – scaler)	Swipe Measurement Area	300 cm <sup>2</sup>
Swipe Measurement	8 counts (1 minute - scaler)	Swipe Material	NSN 6640-00-836-6870
Maximum Permissible Limit (Table 11, 49 CFR 173.433 or Table 5-8 of this report)		660 dpm per 300 cm <sup>2</sup>	

Equation 9-1 is used to calculate net activity concentration on the swipe:

$$C_{\text{Activity}} = \frac{\frac{\text{Gross} - \text{Background}}{\varepsilon * \varepsilon_S}}{A_W}, \quad \text{Equation 9-1}$$

where  $C_{\text{Activity}}$  is the activity concentration,  $\varepsilon$  is detection efficiency,  $\varepsilon_S$  is the swipe collection efficiency (assumed to be 0.25), and  $A_W$  is swiped area. The calculation is completed as follows:

$$C_{\text{Activity}} = \frac{\frac{8 \text{ cpm} - 2 \text{ cpm}}{0.072 * 0.25}}{300 \text{ cm}^2} = 333 \frac{\text{dpm}}{300 \text{ cm}^2}.$$

Since the concentration is below 660 dpm per 300 cm<sup>2</sup>, it meets DOT contamination limits.

(2) Leak Test Pre-Screening. As noted in Table 9-1, AFIOH/SDR, or another NRC-approved laboratory are normally required by AF permit conditions to analyze leak test swipes. It is a recommended practice to screen the sample with a portable radiation detection instrument prior to submission. For this example, assume you are leak testing a sealed  $^{137}\text{Cs}$  source as part of a semi-annual permit requirement. Following the leak test procedures of Table B-1, the compiled measurement information is listed in Table 9-3. The first step is calculation of detection efficiency for the measurement. Table 9-3 lists an efficiency of 0.19 ( $^{99}\text{Tc}$ -2 $\pi$ ). For 4 $\pi$  geometry, the efficiency will be one-half the 2 $\pi$  efficiency, 0.095. Figure B-1 can be used to estimate the detection efficiency for  $^{137}\text{Cs}$  ( $\beta_{\text{max}} = 514 \text{ keV}$ ). Based on the figure and an efficiency of 0.095 for  $^{99}\text{Tc}$ , an estimated detection efficiency for  $^{137}\text{Cs}$  is 0.165. Therefore, the estimated removable activity is:

$$\text{Activity} = \frac{\text{Gross} - \text{Background}}{\varepsilon * \varepsilon_S} = \frac{30 \text{ cpm} - 20 \text{ cpm}}{0.165 * 0.25} = 242 \text{ dpm} = 0.00011 \mu\text{Ci},$$

assuming 0.25 for  $\varepsilon_S$ . The level is below the permit-specified limit of 0.005  $\mu\text{Ci}$ .

TABLE 9-3. Data for  $^{137}\text{Cs}$  Example Leak Test Pre-Screening.

Measurement Instrument	ADM-300 w/ BP-100 Probe	Detection Efficiency (Certificate)	$^{99}\text{Tc}$ : 0.19 (2 $\pi$ )
Background Measurement	20 counts (1 minute – scaler)	Swipe Material	NSN 6640-00-836-6870
Swipe Measurement	30 counts (1 minute - scaler)	Maximum Activity (Permit Condition)	0.005 $\mu\text{Ci}$

While pre-screening sealed-source, leak tests prior to laboratory analysis is recommended, it is impractical to accomplish for some low-energy  $\beta$ -particle emitters like  $^{187}\text{Re}$ ,  $^3\text{H}$ , and  $^{63}\text{Ni}$  because the maximum  $\beta$ -particle energy has insufficient energy to penetrate the entrance window of common pancake G-M probes and the mylar entrance window of  $\alpha/\beta$ -scintillator probes.

### (3) Air Sample Evaluation.

(a) General. Air samples are not routinely measured in AF operations involving RAM, because most operations use sealed sources and those that have unsealed sources generally do not have sufficient potential for aerosol suspension to warrant air sampling. The potential for accident scenarios involving nuclear weapons or other RAM, or a weapons of mass-destruction (WMD) release are the primary reasons BES and CE Readiness maintain air sampling equipment and competence. For many decades, the Staplex<sup>TM</sup> high-volume air samplers with an 8 x 10-inch rectangular filter flange or 4-inch round flange were commonly maintained for nuclear weapon and other accident scenarios. Whatman<sup>TM</sup> #41, or equivalent, cellulose filters were commonly used. Recently, other medium to high-volume samplers have also been maintained for response teams. Many of these accept small diameter (~ 3 – .5 cm) filters, where glass microfiber types are commonly used, because of their high airborne particle retention and better tolerance of humidity. Field analysis of air samples is generally “qualitative” in nature due to many uncertainties to be discussed.

(b) Airborne Particle Retention (APR). The retention of particles on the filter is an important parameter. Generally, it is defined for 0.3  $\mu\text{m}$  diameter particles. The NARP (DoD 2005) refers to this quantity as the collection efficiency,  $E_r$ . The collection efficiency varies dependent on the filter type. Whatman 934-AH Glass Microfiber filters have a collection frequency of 99.8 % for 0.3  $\mu\text{m}$  diameter particles (Whatman 2005). Table B-2 contains APR data for a number of filters.

(c)  $\alpha$ -Particle Absorption Factor. Self-absorption of  $\alpha$ -particle emissions is an important factor in field analysis of filter samples.  $\alpha$ -particle self-absorption can have significant variation based on filter type, humidity, and filter loading. Among these, the two factors that vary by filter type are: density thickness and the penetration depth of particles in the filter. The density thickness within a class of filters (i.e., cellulose) will affect self-absorption, with those of higher density thickness having greater self-absorption. However, penetration depth is even more critical and independent of density thickness when a comparison is made between two classes of filter. For example, Whatman #41 has a density thickness of 8.4  $\text{mg}/\text{cm}^2$  and an  $\alpha$ -particle self-absorption correction of 0.55, while the Whatman 934-AH glass fiber filter has a density thickness of 6.4  $\text{mg}/\text{cm}^2$ , but an estimated self-absorption factor of 0.2.

(d) Filter Size. The dimensions of the filter and detector window determine the calculation and measurement method used. When filters are dimensionally smaller than the detector window, only one measurement is normally required, and detector window and filter areas need not be incorporated into calculations. Whereas, when the filter is dimensionally larger than the detector window, multiple measurements of the filter should be accomplished to account for spatial heterogeneity, detector window and filter areas must be known, and small source detection efficiencies calibrations (that are normally accomplished for most detectors) will be higher than appropriate for the measurement geometry.

(e) Radon Daughter Background Interference. Naturally-occurring background radiations must be accounted for whenever collecting an air sample measurement. Ideally, background should be assessed by an independent air sampler that is likely to have the same background conditions as the air sampler located in the region of suspected airborne contamination. Background  $\alpha$ - and  $\beta$ -particle emitters are primarily from primordial series radionuclides:  $^{238}\text{U}$ ,  $^{232}\text{Th}$ , and their daughters. Normally the largest contributor to background, shortly after the sample is collected, is due to the daughters of  $^{222}\text{Rn}$  (see Table 6-13 for a listing of radionuclides, emissions, and half-lives).  $^{222}\text{Rn}$  daughters have an effective half-life of about 27 minutes, therefore, if samples are re-analyzed after three (3) hours, virtually all the daughters will have decayed. Even if a background air sampling is conducted, it is recommended to re-analyze after three (3) hours for a more accurate assessment. Daughters of  $^{220}\text{Rn}$  have an effective half-life of about 11 hours, requiring about three (3) days for virtually complete decay.  $^{220}\text{Rn}$  daughters are generally a minor contributor to background in comparison to  $^{222}\text{Rn}$  daughters. It is recommended that BES periodically track background count rates on air filter samples in their locality.

(f) Flow Rate Corrections for Pressure and Temperature Changes. Most air sampling equipment measure flow rate with integral flow rate meters that are dependent on ambient atmospheric pressure and temperature. This is true for the Staplex Model TFIA High Volume Air Sampler's used by BES. Flow rate meters, commonly referred to as "rotameters" must be periodically calibrated, with calibration certificates noting pressure and temperature that existed during calibration. Calibration certificates should provide a graph or equation that relates the displayed rotameter flow rate to a reported flow rate. This is important since the displayed flow rate of most rotameters can be changed by adjusting a fitting on the top of the rotameter without any real change in flow rate. Thus, the rotameters only provide relative flow rate. The Staplex Model TFIA has a brass screw that allows adjustment of the rotameter, but should never be adjusted by field personnel since it will invalidate the calibration graph or equation. Additionally, if air sampling is conducted when air pressure or temperature is significantly different than that existing during calibration, corrections must be made according to equation 9-2:

$$FR_{Actual} = FR_{reported} \sqrt{\frac{P_{Cal} * T_{Amb}}{P_{Amb} * T_{Cal}}}, \quad \text{Equation 9-2}$$

where  $P_{Cal}$ ,  $T_{Cal}$ ,  $P_{Amb}$ , and  $T_{Amb}$  are the respective pressures and temperature during calibration and ambient during sampling, and  $FR_{Reported}$  is the reported flow rate during sampling and  $FR_{Actual}$  is the actual (i.e., corrected) flow rate. If air pressure data is not available, corrections based on altitude-specific mean pressure are recommended for use as listed in Table 9-4. Temperature correction

factors are listed in Table 9-5. If both pressure and temperature corrections are necessary, the product of the two corrections factors is appropriate. From Table 9-4, it is apparent that pressure corrections are less than 5 % if the altitude difference is less than 3000 feet, making pressure corrections unnecessary for most BES measurements conditions. As well, unless there is at least a 40 °F difference in temperature, corrections will be minor. Since rotameters use gravitation force for proper operation, during use, rotameters must be positioned perpendicular to ground level.

TABLE 9-4. Flow Rate Pressure Correction Factors Based on Mean Pressure at Various Altitudes for Common Rotameter Type Air Sampler Flow Gauges.

		Altitude When Calibrated (feet)										
		0	1000	2000	3000	4000	5000	6000	7000	8000	9000	10000
Altitude When Used (feet)	0	1	0.984	0.969	0.952	0.936	0.919	0.902	0.884	0.867	0.849	0.830
	1000	1.016	1	0.984	0.969	0.952	0.936	0.919	0.902	0.884	0.867	0.849
	2000	1.032	1.016	1	0.984	0.969	0.952	0.936	0.919	0.902	0.884	0.867
	3000	1.050	1.032	1.016	1	0.984	0.969	0.952	0.936	0.919	0.902	0.884
	4000	1.069	1.050	1.032	1.016	1	0.984	0.969	0.952	0.936	0.919	0.902
	5000	1.088	1.069	1.050	1.032	1.016	1	0.984	0.969	0.952	0.936	0.919
	6000	1.11	1.088	1.069	1.050	1.032	1.016	1	0.984	0.969	0.952	0.936
	7000	1.13	1.11	1.088	1.069	1.050	1.032	1.016	1	0.984	0.969	0.952
	8000	1.15	1.13	1.11	1.088	1.069	1.050	1.032	1.016	1	0.984	0.969
	9000	1.18	1.15	1.13	1.11	1.088	1.069	1.050	1.032	1.016	1	0.984
	10000	1.20	1.18	1.15	1.13	1.11	1.088	1.069	1.050	1.032	1.016	1

TABLE 9-5. Flow Rate Temperature Correction Factors for Common Rotameter Type Air Sampler Flow Gauges.

		Temperature When Calibrated (°F)					
		40	50	60	70	80	90
Temperature When Used (°F)	-10	0.95	0.94	0.87	0.92	0.91	0.91
	0	0.96	0.95	0.94	0.87	0.92	0.92
	10	0.97	0.96	0.95	0.94	0.87	0.92
	20	0.98	0.97	0.96	0.95	0.94	0.87
	30	0.99	0.98	0.97	0.96	0.95	0.94
	40	1	0.99	0.98	0.97	0.96	0.95
	50	1.01	1	0.99	0.98	0.97	0.96
	60	1.02	1.01	1	0.99	0.98	0.97
	70	1.03	1.02	1.01	1	0.99	0.98
	80	1.04	1.03	1.02	1.01	1	0.99
	90	1.05	1.04	1.03	1.02	1.01	1
	100	1.06	1.05	1.04	1.03	1.02	1.01
	110	1.07	1.06	1.05	1.04	1.03	1.02

(g) Example for Air Filter Dimension Smaller than Probe Entrance Window. For this example, assume that you are providing air sampling at a nuclear weapons accident, where  $^{239+240}\text{Pu}$  is the suspected airborne contaminant. Table 9-6 contains measurement information. Assuming that specific  $\alpha$ -particle self-absorption information is not available, conservatively, 80 % is used for a glass fiber filter, making the  $\alpha$ -particle correction factor 20 % and the corrected detection efficiency, 0.036. Equation 9-3 is used to calculate the concentration.

$$C_{\text{Activity}} = \frac{\text{Count Rate}}{\varepsilon * \text{AFR} * \text{APR} * T}, \quad \text{Equation 9-3}$$

where  $C_{\text{Activity}}$  is the activity concentration,  $\varepsilon$  is detection efficiency, AFR is average flow rate, APR is the airborne particle retention, and  $T$  is air sampling time. The calculation is completed as follows for the background air sample:

$$C_{\text{Activity}} = \frac{45 \text{ cpm}}{0.036 * \frac{12 \text{ ft}^3}{\text{min}} * 120 \text{ min}} = \frac{0.87 \text{ dpm}}{\text{ft}^3}.$$

Table 9-6. Data for  $^{239+240}\text{Pu}$  Example Air Sample Analysis.

Measurement Instrument	ADM-300 w/ AP-100 Probe	Detection Efficiency (Certificate)	$^{239}\text{Pu}$ : 0.18 (4 $\pi$ )
Background Air Sampler Measurement (t=0 hr, post sampling)	45 counts (1 minute – scaler)	Contamination Zone Air Sampler Measurement (t=0 hr, post sampling)	115 counts (1 minute – scaler)
Background Air Sampler Average Flow Rate	12 ft <sup>3</sup> /min	Contamination Zone Air Sampler Average Flow Rate	9 ft <sup>3</sup> /min
Background Air Sampler Sample Time	120 min	Contamination Zone Air Sampler Sample Time	100 min
Filter Material (density thickness)	Whatman 934-AH (6.4 mg/cm <sup>2</sup> )	Air Sample Filter Dimensions	Round (3 cm diameter)
Airborne Particle Retention	0.998	Air Sample Filter Area	7.1 cm <sup>2</sup>

Using the same formula for the air sampler located in the contaminated zone yields 3.6 dpm/ft<sup>3</sup>, and the net is 2.7 dpm/ft<sup>3</sup>. Using the volumetric-concentration conversion factors in Table B-3, the net activity concentration is 94 dpm/m<sup>3</sup>. Table B-4 contains recommended respiratory protection levels for emergency workers from the NARP (DoD 2005).

(h) Example for Air Filter Dimension Larger than Probe Entrance Window. For this example, assume that you are providing air sampling for a DU machining operation, where airborne

contamination is possible. Table 9-7 contains measurement information. Equation 9-4 is used to calculate activity concentration,

$$C_{\text{Activity}} = \frac{\text{Count Rate}}{\varepsilon * \text{AFR} * \text{APR} * T} * \frac{A_f}{A_p}, \quad \text{Equation 9-4}$$

where  $C_{\text{Activity}}$  is the activity concentration,  $\varepsilon$  is detection efficiency, AFR is average flow rate, APR is the airborne particle retention,  $T$  is air sampling time,  $A_f$  is filter area, and  $A_p$  is probe entrance window area. The calculation for the background air sample as measured with the AP-100 probe is:

$$C_{\text{Activity}} = \frac{43 \text{ cpm}}{0.0825 * \frac{50 \text{ ft}^3}{\text{min}} * 0.72 * 180 \text{ min}} * \frac{406 \text{ cm}^2}{123 \text{ cm}^2} = \frac{0.27 \text{ dpm}}{\text{ft}^3},$$

using a corrected detection efficiency of 0.0825, based on a large area calibration source detection efficiency of 0.15 and an  $\alpha$ -particle self-absorption correction factor of 0.55 (Table B-2).

Calculation of  $\beta$ -particle detection efficiency requires evaluation of the  $\beta$ -particle emissions for DU. Assuming that the DU is moderately-depleted, as in Table 6-1, only the 2.28 MeV (82 % frequency) and 0.189 MeV (59 % frequency) have sufficient energy to penetrate the BP-100 entrance window or a sufficiently high emission frequency. Using Figure B-1, the mean  $\beta$ -particle detection efficiency is 0.17. Table 9-8 contains a summary of the calculations for the data in Table 9-7.

TABLE 9-7. Data for Depleted Uranium Example Air Sample Analysis.

Measurement Instrument	ADM-300 with AP-100 and BP-100 Probes	Detection Efficiency (Certificate)	$^{239}\text{Pu}$ ( $\alpha$ ): 0.15 (4 $\pi$ -large area) $^{99}\text{Tc}$ ( $\beta$ ): 0.095 (4 $\pi$ )
Mean Background Air Sampler Measurement (t=3 hr, post sampling)	43 counts (AP-100) (1 minute – scaler)	Mean Contamination Zone Air Sampler Measurement (t=3 hr, post sampling)	105 counts (AP-100) (1 minute – scaler)
	29 counts (BP-100) (1 minute – scaler)		47 counts (BP-100) (1 minute – scaler)
Background Air Sampler Average Flow Rate	50 ft <sup>3</sup> /min	Contamination Zone Air Sampler Average Flow Rate	45 ft <sup>3</sup> /min
Background Air Sampler Sample Time	180 min	Contamination Zone Air Sampler Sample Time	150 min
Filter Material (density thickness)	Whatman #41 (8.4 mg/cm <sup>2</sup> )	Air Sample Filter Dimensions (Area)	Rectangular (8"x10") (406 cm <sup>2</sup> )*
Airborne Particle Retention (APR)	0.72 (~ 1 $\mu\text{m}$ ), Table B-2 (OEHL 1983)	Probe Entrance Window Area	123 cm <sup>2</sup> (AP-100) 15.5 cm <sup>2</sup> (BP-100)

TABLE 9-8. Summary of Activity Concentrations for Data in Table 9-7.

Measurement Probe	Corrected Detection Efficiency	Contamination Zone	Background	Net
		dpm/ft <sup>3</sup> (μCi/ml*)		
AP-100	0.036	0.86	0.27	0.60 ( $9.6 \times 10^{-12}$ )
BP-100	0.17	1.5	0.69	0.81 ( $1.3 \times 10^{-11}$ )

\* Using conversion factor from Table B-3.

(i) Interpretation of DU Air Sampling Data. The interpretation of air sampling data with respect to regulatory limits is an important step in the hazard evaluation process. For the DU example, assume that it is NRC-licensed material and permitted through the AF RIC. In this case, airborne concentration limits [referred by the NRC as derived air concentration (DAC)] of 10 CFR 20, Appendix B, Table 1, Column 3 should be used. DACs are based on a 2000 hr/yr worker exposure, with a 1.2 m<sup>3</sup>/hr breathing rate. The DAC for uranium dioxide (UO<sub>2</sub>) is  $2 \times 10^{-11}$  μCi/ml (10 CFR 20, 1 January 2004). To evaluate the α- and β-particle emissions with respect to the limits, it is important to know the emission frequency. From Table 6-1, an α-particle is emitted for every uranium atom decay in DU, thus the net α-particle concentration from Table 9-8 can be assumed to be equal to the DU activity concentration. For the β-particle emissions discussed above, we assumed that only the 2.28 and 0.189 MeV β-particles were detectable with the BP-100 probe, and the estimated composite detection efficiency for these was 0.17. Therefore, the frequency of detectable β-particle emissions per DU decay (i.e., the 2.28 and 0.189 MeV particles) is 1.41 [see para. 9.3.(h)] and the estimated DU activity concentration is 0.57 μCi/ml. The estimated DU activity concentration is below  $2 \times 10^{-11}$  μCi/ml, regardless of the emission being evaluated.

(j) α-, β-, or α- and β-Particle Analysis?. In the last example, both the α- and β-particle emissions were evaluated for the contaminant because DU emits both, and the combined information is more valuable than either one alone due to uncertainties in detection efficiency, influence of background radiations, etc. For measurements of unknown contaminants, it is always recommended to assess both emissions because the combined data can be used in conjunction with information from other analyses, like γ-spectroscopy, to aid in proper identification.

(k) Key Parameters for Air Sampling. Air sampling is one of the most important radiological surveillance activities that is conducted during a response to an airborne release of radioactive material in an incident/accident. As discussed, there is uncertainty in some of the parameters necessary for field assessment. Follow-up with laboratory analysis is recommended in most situations and required by regulations for some samples. Over the last few decades, there has been a number of field guides to aid AF and DoD radiological incident responders (Nichelson 2004, ACC 2000, DoD 2005, Scott 1983). Among these important guidance documents, there is extensive procedural information on air sampling and associated parameters. These documents are not always in agreement on suggested values for some parameters and some of the guides have incorrect constants. For example, IOH-SD-BR-CL-2004-0058 (Nichelson 2004) and the ACC Bioenvironmental Field Manual 00-1 (ACC 2000) use the active detection area (92 cm<sup>2</sup>) of the ADM-300 AP-100 probe, while it is appropriate to use the total entrance window area, 123 cm<sup>2</sup>,

since calibration sources encompass both active (open mylar areas) and covered (mylar areas covered by protective aluminum grid) areas. While discrepancies of this type may be of concern to individual users, it must be remembered that many of the parameters are estimates, and field analysis of air samples only provide an estimate of airborne concentrations. As well, neglecting to recount the filter sample more than three (3) hours post air sampling, could introduce uncertainty in proportion to that attributed to uncertainties in some parameters and small errors in some constants. Laboratory analysis, at a later time, will have inherently lower uncertainty and bias, if adequate information is provided to the laboratory. As such, it is important for personnel in the field to keep track of key parameters necessary for laboratory analysis: the type of filter used and its APR, total volume collected, collection time, suspected contaminant, and field estimate of activity.

#### (4) Surface Contamination Evaluation.

(a) General. Current operations involving unsealed RAM, contamination from past operations, or leaking sources (i.e.,  $^{226}\text{Ra}$ ) may require assessment of surface contamination. Section 5 discussed some standards and guideline for surface contamination. Two types of surface contamination are generally evaluated: removable and fixed contamination. Since fixed contamination is generally assessed *in-situ* (in place), measurements will include both the fixed and removable components. The combined contamination is referred to as "total." Because an example was already provided on removable contamination, only an example of total contamination will be provided here.

(b) *In-Situ* Measurement Efficiency. Selection or determination of an appropriate measurement efficiency is problematic for *in-situ* measurement of  $\alpha$ -particle and low-energy  $\beta$ -particle emissions. In previous parts of this section, it was noted that Whatman #41 paper and a glass fiber filter had  $\alpha$ -particle self-absorption factors of 45 and 80 %, respectively. Self-absorption factors for surfaces will be highly dependent on the type of surface and nature of the contaminant. For example, in general, rough surfaces like concrete will have higher self-absorption than a smooth surface like linoleum or painted materials. Contaminants that have existed on surfaces for long periods of time may have higher self-absorption than freshly-deposited contaminants because the longer contact times may afford greater penetration. Without specific information about a contaminated surface, it is best to make a conservative assumption regarding  $\alpha$ - or low-energy  $\beta$ -particle self-absorption. Values in the range of 90 to 95 % are fairly conservative for most applications. For regulatory compliance measurements in some decommissioning activities, special studies to estimate efficiencies may be warranted. These studies may involve destruction of test surface areas and laboratory analyses of removed surface material.

(c) Example. Assume that you are applying Reg. Guide 1.86, acceptable surface contamination limits (Table 5-4) to old  $^{226}\text{Ra}$  contamination on a concrete surface. Table 9-9 contains measurement information. Measurements were conducted for both  $\alpha$ - and  $\beta$ -particle emissions, and at multiple locations within  $1\text{ m}^2$ . Equation 9-5 is used for the calculation:

$$C_{\text{Activity}} = \frac{\text{Gross - Background}}{A_S \cdot \varepsilon}, \quad \text{Equation 9-5}$$



where  $C_{\text{Activity}}$  is the activity concentration,  $\epsilon$  is detection efficiency, and  $A_S$  is the sampling area. This equation is similar to Equation 9-1, except that  $A_W$ , the swipe area, is replaced by  $A_S$ . For measurements collected with the BP-100 probe (pancake G-M),  $A_S$  is set at  $15.5 \text{ cm}^2$ , the probe entrance window area. However, for compliance with the maximum acceptable surface contamination level for the AP-100 probe,  $100 \text{ cm}^2$  is used in lieu of  $123 \text{ cm}^2$ , the entrance window area, because Reg. Guide 1.86 specifies  $100 \text{ cm}^2$  as the maximum area for this measurement. For the average concentration measurement,  $123 \text{ cm}^2$  is used, since averaging over  $1 \text{ m}^2$  is allowed. For measurement location #1 ( $\alpha$ ), the calculation is as follows:

$$C_{\text{Activity}} = \frac{\frac{4 - 2 \text{ cpm}}{0.015}}{100 \text{ cm}^2} = \frac{133 \text{ cpm}}{100 \text{ cm}^2},$$

where the  $\alpha$ -particle self-absorption factor is assumed to be 90 %, making the  $\alpha$ -particle correction factor 10 % and the corrected detection efficiency is 0.015. Table 9-10 summarizes how an estimate of  $\beta$ -particle detection efficiency can be calculated for the major emissions from the  $^{226}\text{Ra}$   $\beta$ -emitting daughters. Since the listed emissions are medium to high energy, self-absorption should be minimal.

TABLE 9-9. Data for  $^{226}\text{Ra}$  Example Surface Contamination.

Measurement Instrument	ADM-300 with AP-100 and BP-100 Probes	Detection Efficiency (Certificate)	$^{239}\text{Pu}$ ( $\alpha$ ): 0.15 ( $4\pi$ -large area) $^{99}\text{Tc}$ ( $\beta$ ): 0.095 ( $4\pi$ )
Mean Background Measurement	2 counts (AP-100) (1 minute – scaler)	Suspected Contamination Location #1	4 counts (AP-100) (1 minute – scaler)
	19 counts (BP-100) (1 minute – scaler)		21 counts (BP-100) (1 minute – scaler)
Suspected Contamination Location #2	24 counts (AP-100) (1 minute – scaler)	Suspected Contamination Location #3	102 counts (AP-100) (1 minute – scaler)
	25 counts (BP-100) (1 minute – scaler)		33 counts (BP-100) (1 minute – scaler)
Suspected Contamination Location #4	77 counts (AP-100) (1 minute – scaler)	Probe Entrance Window Area	$123 \text{ cm}^2$ (AP-100) $15.5 \text{ cm}^2$ (BP-100)
	29 counts (BP-100) (1 minute – scaler)		

Table 9-11 contains summary calculations and acceptable levels from Reg. Guide 1.86. In comparison of the  $\alpha$ - and  $\beta$ -particle measurements, it is clear that the net  $\alpha$ -emissions are significantly higher than the  $\beta$ -emissions, though the  $^{226}\text{Ra}$  decay chain has four  $\alpha$ -particle emissions to two  $\beta$ -emissions. This suggests that the daughters may not be in equilibrium with the  $^{226}\text{Ra}$  parent. This would not be unusual for this type of contaminant, since  $^{222}\text{Rn}$  is a gas and can readily

TABLE 9-10.  $\beta$ -Particle Efficiency Estimate for  $^{226}\text{Ra}$  Emitting Daughters  
(Radionuclide Data from Table 6-13 and Efficiency Data from Table B-1.

$\beta$ -Particle Energy (MeV)	Emission Frequency	Estimated Efficiency	$\beta$ -Particle Energy (MeV)	Emission Frequency	Estimated Efficiency
0.65	0.5	0.17	1.0	0.23	0.19
0.71	0.4	0.175	1.51	0.4	0.22
0.98	0.06	0.19	3.26	0.19	0.26
Overall		0.195			

diffuse from the surface prior to decay since it has a radiological half-life of 3.82 days. Therefore, the  $\alpha$ -particle measurement data is more appropriate for comparison to the levels specified in Table 9-7. In comparison, all but measurement location #1 had contamination level in excess of the maximum contamination limit. The average of the four measurement locations is greater than the Reg. Guide 1.86 level for concentrations averaged over  $1\text{ m}^2$ . While not included in this example, removable contamination should be assessed since the total measured activity concentrations are in excess of removable contamination limits.

TABLE 9-11. Summary Calculations and Reg. Guide 1.86 Levels for Data from Table 9-7.

Location	Limit	dpm/min per $100\text{ cm}^2$		
		Net $\alpha$ -Particle	Net $\beta$ -Particle	Reg. Guide 1.86 Level
#1	Maximum	133	66	300
#2	Maximum	1467	199	
#3	Maximum	6667	463	
#4	Maximum	5000	331	
Overall	Average	2696	265	100

## 10. Department of Transportation Package Shipping and Receipt.

a. General. DOT specifies requirements for transport of RAM on publicly-accessible roads and highways, U.S. Mail, and private-sector carriers whether over roads or air. A notable exception to this is the transport of RAM on military air (MILAIR) between military installations. This section of the report should be used as an aid to individuals that have had some DOT RAM shipping and receipt training. Since most shipments aided by BES are for "excepted packages," the information in this section will focus on these types of shipments. Additional assistance should be received from AFIOH/SDR if complex shipments are planned.

### b. DOT Terms and Definitions.

(1)  $A_1$  – maximum activity of special form Class 7 (radioactive) material permitted in a Type A package.

(2)  $A_2$  – maximum activity of Class 7 (radioactive) material permitted in a Type A package.

(3) Cosignee – the person of place shown on a shipping document, package marking, or other media as the location to which a carrier is directed to transport a hazardous material.

(4) Exemption Value – an exempt material activity concentration or an exempt consignment activity limit listed in Table in 49 CFR 173.436.

(5) Excepted Package – a package with its excepted Class 7 (radioactive) materials.

(6) Hazardous Material – a material which has been designated to pose an unreasonable risk to health, safety, and property when transported in commerce (Table in 49 CFR 172.101).

(7) Hazardous Substance – a material that is listed in Appendix A to 49 CFR 172.101 and is in a quantity in one package that equals or exceeds the reportable quantity (RQ) limit listed in Appendix A to 172.101.

(8) Limited Quantity of Class 7 (radioactive) Material – quantity of material that doesn't exceed package limits in 49 CFR 173.425 & .421.

(9) Package – package with radioactive contents.

(10) Class 7 Radioactive Material – any material containing radioactive material where both activity concentration and total activity exceed values in Table of 49 CFR 173.436 or instructions in 173.

(11) Radioactive Instruments and Articles – any manufactured instrument or article or similar instrument in gaseous or non-dispersible solid form as a component part.

(12) Special Form Class 7 (radioactive material) – indispersible or sealed radioactive material meeting DOT requirements.

(13) Radioactive Material – means any material containing radionuclides where both the activity concentration and the total activity in the consignment exceed the values in Table of Section 173.436 or values according to the instructions in Section 173.444.

c. Eight Steps in Preparing a Package for Shipment. This report will list eight primary steps in preparing RAM for shipment. For individuals experienced in shipping RAM, use of this guide may be limited to some of the tabular data. Appendix B, Table B contains a shipment quality assurance checklist for excepted quantity RAM (Mays 2005). Updates to this form and Type A quantity forms should be available through internet access to 88 ABW/EM.

(1) Identify Radionuclides and Activities (Step 1). The radionuclides and associated activities must be identified as a first step. For some radionuclides that have relatively short half-lives, decay-correction calculations can be performed to estimate the activity at the time of shipment.

(2) Determine Whether the Material meets DOT Hazardous Material Definitions (Step 2).

(a) Are the Radionuclides in the Consignment DOT Defined Radioactive Material?

Table 10-1 contains the DOT criteria for exempting radionuclides from DOT defined radioactive material.

TABLE 10-1. Selected Radionuclides from Table in 49 CFR 173.436, Exempt Material Activity Concentrations and Consignment Activity Limits (1 Oct 04).

Radionuclide	Exempt Activity Concentration Limit (Ci/g)	Exempt Activity Limit (Ci)	Radionuclide	Exempt Activity Concentration Limit (Ci/g)	Exempt Activity Limit (Ci)
H-3	$2.7 \times 10^{-5}$	$2.7 \times 10^{-2}$	I-131	$2.7 \times 10^{-9}$	$2.7 \times 10^{-5}$
C-14	$2.7 \times 10^{-7}$	$2.7 \times 10^{-4}$	Cs-137*	$2.7 \times 10^{-10}$	$2.7 \times 10^{-4}$
P-32	$2.7 \times 10^{-8}$	$2.7 \times 10^{-6}$	Pm-147	$2.7 \times 10^{-7}$	$2.7 \times 10^{-7}$
Fe-55	$2.7 \times 10^{-7}$	$2.7 \times 10^{-5}$	Re-187	$2.7 \times 10^{-5}$	$2.7 \times 10^{-2}$
Co-57	$2.7 \times 10^{-9}$	$2.7 \times 10^{-5}$	Tl-201	$2.7 \times 10^{-9}$	$2.7 \times 10^{-5}$
Co-60	$2.7 \times 10^{-10}$	$2.7 \times 10^{-6}$	Po-210	$2.7 \times 10^{-10}$	$2.7 \times 10^{-7}$
Ni-63	$2.7 \times 10^{-6}$	$2.7 \times 10^{-3}$	Ra-226*	$2.7 \times 10^{-10}$	$2.7 \times 10^{-7}$
Ga-67	$2.7 \times 10^{-9}$	$2.7 \times 10^{-5}$	Th-230	$2.7 \times 10^{-11}$	$2.7 \times 10^{-7}$
Kr-85 (gas)	$2.7 \times 10^{-6}$	$2.7 \times 10^{-7}$	Th-232	$2.7 \times 10^{-10}$	$2.7 \times 10^{-7}$
Sr-90*	$2.7 \times 10^{-9}$	$2.7 \times 10^{-7}$	<sup>En</sup> U ( $\leq 20\%$ )	$2.7 \times 10^{-11}$	$2.7 \times 10^{-8}$
Y-90	$2.7 \times 10^{-8}$	$2.7 \times 10^{-6}$	DU	$2.7 \times 10^{-11}$	$2.7 \times 10^{-8}$
Mo-99	$2.7 \times 10^{-9}$	$2.7 \times 10^{-5}$	<sup>Nat</sup> U**	$2.7 \times 10^{-11}$	$2.7 \times 10^{-8}$
Tc-99m	$2.7 \times 10^{-9}$	$2.7 \times 10^{-4}$	Pu-238	$2.7 \times 10^{-11}$	$2.7 \times 10^{-7}$
Pd-103	$2.7 \times 10^{-8}$	$2.7 \times 10^{-3}$	Pu-239	$2.7 \times 10^{-11}$	$2.7 \times 10^{-7}$
Cd-109	$2.7 \times 10^{-7}$	$2.7 \times 10^{-5}$	Pu-240	$2.7 \times 10^{-11}$	$2.7 \times 10^{-7}$
In-111	$2.7 \times 10^{-9}$	$2.7 \times 10^{-5}$	Am-241	$2.7 \times 10^{-11}$	$2.7 \times 10^{-7}$
I-125	$2.7 \times 10^{-8}$	$2.7 \times 10^{-5}$			

\* Includes radioactive daughters in secular equilibrium.

\*\* Slow lung absorption – UO<sub>2</sub>, U<sub>3</sub>O<sub>8</sub> & metallic forms.

If either criterion is met, the material is classified as exempt. For mixtures of radionuclides, the sum of the fractions rule applies. Most of the common items that BES assist in shipping will not meet either exemption criterion.

(b) Is the Material Defined as a DOT Hazardous Substance? To determine whether the contents of a package have a reportable quantity (RQ) of RAM, the limits of Table 10-2 must be applied. For mixtures of radionuclides, the sum of the fractions rule applies. In general, for most small source shipments that BES will assist in preparation, will not have a reportable quantity of RAM. A notable exception is Troxler<sup>TM</sup> and some Niton<sup>TM</sup> gauges that contain more than 0.01 Ci of <sup>241</sup>Am. If the package contents have a RQ of RAM, the package requires an "RQ" marking and the paperwork enclosed with the package requires an "RQ" annotation.

TABLE 10-2. Selected Radionuclides from Table 2, Appendix A, 49 CFR 172.101, Hazardous Substance Reportable Quantity (RQ) Limit (1 Oct 04).

Radionuclide	Reportable Quantity (Ci)	Radionuclide	Reportable Quantity (Ci)	Radionuclide	Reportable Quantity (Ci)
H-3	100	Tc-99m	100	Th-230	0.01
C-14	10	Pd-103	100	Th-232*	0.001
P-32	0.1	Cd-109	1	U-234*	0.1
Fe-55	100	In-111	100	U-235*	0.1
Co-57	100	I-125	0.01	U-238*	0.1
Co-60	10	I-131	0.01	<sup>En</sup> U (≤ 20 %)	Para. 7, App A 172.101
Ni-63	100	Cs-137	1	DU	
Ga-67	100	Pm-147	10	<sup>Nat</sup> U*	0.1
Kr-85 (gas)	1000	Re-187	1000	Pu-238	0.01
Sr-90	0.1	Tl-201	1000	Pu-239	0.01
Y-90	10	Po-210	0.01	Pu-240	0.01
Mo-99	100	Ra-226*	0.1	Am-241	0.01

\* Includes radioactive daughters in secular equilibrium.

(3) Classify the Material. If the material is not an exempt concentration and/or quantity, based on the criteria in the Table of 49 CFR 173.436, then DOT classifies the material as "Class 7 (radioactive) Material."

(4) Calculate DOT Shipping Quantity. DOT has a number of categories of Class 7 (radioactive) Material, based on the radionuclide, whether it is integral component part to an instrument or article, and the total quantity. Among the categories:

- excepted quantity,
- low specific activity/surface contaminated object
- highway route controlled quantity, and
- Type A quantity,
- Type B quantity,
- Fissile/Fissile Excepted,

most RAM shipments that BES will aid in preparation are excepted quantity, Type A quantity, and fissile exempt. As such, this report will provide information on these types of shipments. Other shipments are likely to be conducted under contract, where sufficient technical experience with DOT shipments exists.

(a) Excepted Quantities. Packages containing excepted quantities of RAM have relief from a number of requirements that exist for Type A and B quantities. Most excepted quantity shipments in the AF will be:

- limited quantity and
- instruments and articles.

Table 5-10 contains activity limits for limited quantities, and instruments and articles based on  $A_1$  and  $A_2$  values from Table 5-11. Table 10-3 contains a summary of limits for common AF radionuclides. Instrument and articles are manufactured devices like electronic tubes, watches, clocks, exit signs, compasses, or similar in non-dispersible solid or gaseous forms.

TABLE 10-3. DOT activity Limits for Limited Quantities, and Instruments and Articles for Radionuclides Common to AF Operations.

Radionuclide	Special Form (Curies)			Normal Form (Curies)		
	Instrument & Articles		Limited Quantity	Instrument & Articles		Limited Quantity
	Instrument Limit	Package Limit		Instrument Limit	Package Limit	
H-3*	NA	NA	NA	22	220	22
H-3 (gas)	1.1	11	1.1	1.1	11	1.1
C-14	11	1100	1.1	0.81	81	0.081
Fe-55	11	1100	1.1	11	1100	1.1
Co-57	2.7	270	0.27	2.7	270	0.27
Co-60	0.11	11	0.011	0.11	11	0.011
Ni-63	11	1100	1.1	8.1	810	0.81
Kr-85 (gas)	0.27	2.7	0.27	0.27	2.7	0.27
Sr-90	0.081	8.1	$8.1 \times 10^{-3}$	0.81	8.1	$8.1 \times 10^{-3}$
Y-90	0.081	8.1	$8.1 \times 10^{-3}$	0.81	8.1	$8.1 \times 10^{-3}$
Cd-109	8.1	810	0.81	0.54	54	0.054
Cs-137	0.54	54	0.054	0.16	16	0.016
Pm-147	11	1100	1.1	8.1	810	0.81
Po-210	11	1100	1.1	$5.4 \times 10^{-3}$	0.54	$5.4 \times 10^{-4}$
Ra-226	0.054	5.4	0.0054	$8.1 \times 10^{-4}$	0.081	$8.1 \times 10^{-5}$
<sup>Nat</sup> U, Th-232, Re-187, DU	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited
Pu-238, Pu-239, & Pu-240	2.7	270	0.27	$2.7 \times 10^{-4}$	0.027	$2.7 \times 10^{-5}$
Am-241	2.7	270	0.27	$2.7 \times 10^{-4}$	0.027	$2.7 \times 10^{-5}$

\* In activated luminous paint and tritium adsorbed on solid carriers.

Manufactured articles are another category of excepted Class 7 (radioactive) material that contain natural uranium and thorium, provided that the RAM is enclosed in an inactive sheath made of metal or other protective material.

(b) Type A Quantities. Quantities of radioactive material that are less than or equal to appropriate  $A_1$  and  $A_2$  values of Table 5-11, but do not qualify as excepted quantities are Type A quantities. The most common Type A quantities that BES will likely aid in preparation are: Troxler<sup>TM</sup> gauges, irradiator sources like  $^{60}\text{Co}$  or  $^{137}\text{Cs}$ , and nuclear medicine pharmaceuticals. Type A quantity packages require shipping papers and labels that are normally not required for excepted package shipments.

(c) Fissile Material. RAM containing  $^{238}\text{Pu}$ ,  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$ ,  $^{233}\text{U}$ ,  $^{235}\text{U}$ , or any combination of these are fissile material. Specifically excluded are  $^{\text{Nat}}\text{U}$  and DU. 49 CFR 173.453 (1 Oct 04) lists six (6) exceptions to the requirements for shipping these radionuclides under the fissile materials rule. 49 CFR 173.453(a) excepts packages if they contain less than 2 grams (g) of these isotopes. It is unlikely that BES will have shipments exceeding this value.

(5) Selecting the DOT Shipping Name. Table 10-4 contains DOT shipping names that are

TABLE 10-4. DOT Shipping Names for Common AF Shipments (40 CFR 172.101, 1 Oct 04).

Class 7 Quantity	Reportable Quantity (RQ)	Shipping Name and ID Number
Excepted-Instrument or Article	No	Radioactive material, excepted package-instrument or articles, Class 7, UN2911
	Yes	Radioactive material, excepted package-instrument or articles, Class 7, UN2911, RQ
Excepted-Limited Quantity	No	Radioactive material, excepted package-limited quantity, Class 7, UN2910
	Yes	Radioactive material, excepted package-limited quantity, Class 7, UN2910, RQ
Excepted-Manufactured Articles	No	Radioactive material, excepted package-articles manufactured from natural uranium or depleted uranium or natural thorium, Class 7, UN2909
	Yes	Radioactive material, excepted package-articles manufactured from natural uranium or depleted uranium or natural thorium, Class 7, UN2909, RQ
Type A Special Form	No	Radioactive material, Type A package, special form non-fissile or fissile excepted, Class 7, UN 3332
	Yes	Radioactive material, Type A package, special form, non-fissile or fissile excepted, Class 7, UN 3332, RQ
Type A Normal Form	No	Radioactive material, Type A package, non-special form, non-fissile or fissile excepted, Class 7, UN 2915
	Yes	Radioactive material, Type A package, non-special form, non-fissile or fissile excepted, Class 7, UN 2915, RQ

common to shipments that BES will aid in preparation. For Type B shipments (i.e. those with quantities exceeding Type A package limits) and fissile materials, BES should receive assistance from AFIOH/SDR and/or individuals with sufficient DOT transportation experience.

(6) Package Selection. The type of package used for RAM shipments is dependent on the DOT Class 7 (radioactive) material quantity. DOT has a number of applicable rules for packages. Table 10-5 contains a summary of DOT rule paragraph numbers as applicable to the quantity.

TABLE 10-5. DOT Package Requirements (49 CFR, 1 Oct 04).

Rule	Excepted Packages			Type A Non-Fissile
	Instrument & Articles	Limited Quantity	Manufactured Articles	
173.24, 173.24a, 173.24b, 173.410	X	X	X	X
173.421		X		
173.422	X	X	X	
173.424	X			
173.426			X	
173.412, 173.415				X

(a) Excepted Packages. Based on the above rules, these are key requirements for packages:

- no identifiable release of hazardous material to the environment from insults normal to transportation,
- package shall be able to withstand impact, temperature changes, humidity, vibrations, etc. normal to transportation,
- easily handled and secured during transport, and
- external source, as far as practicable, will be free from protruding features and will be easily decontaminated.

Many of the instruments and articles that are routinely transported in the AF are shipped in instrument cases with foam inserts (i.e., durable plastic cases) and durable cardboard boxes with foam peanuts, foam padding, etc.

(b) Type A Packages. Type A packages have a number of requirements above that of those that exist for excepted packages like package seals to verify that a package has not been opened during transit, minimum external dimensions, performance testing, and containment systems for normal form contents. Almost all Type A quantity shipments that BES will aid in preparation will have a manufacturer-provided, Type A container or the source will be integral to its Type A container (common to many irradiator sources). Type A design information and testing results should accompany a container and should be retained on file by the possessing organization.



(7) Identify and Assess Maximum Radiation and Contamination Limits. All Class 7 (radioactive) materials require dose-equivalent assessments and removable contamination assessments. Table 5-7 contains dose-equivalent limits for excepted and other packages that require labeling. From the table, instrument or articles require two separate assessments: one at 10 cm from the surface of unpackaged instrument or articles and another at any location on the external surface of the package. For excepted packages of limited quantities or manufactured articles, only the external surface assessment is required. For other quantities of RAM, two dose-equivalent assessments are required: one at any location on the external surface of the package, and another at one (1) meter from the package surface that is termed the "Transport Index" and listed in units of mrem/hr. Contamination limits are listed in Table 5-8, with an example being provided in Para. 9.d.(1).

(8) Determine and Apply Communications to the Package. Communications that must accompany packages consist of many items from labels, shipping papers, external package markings, internal package markings, placards, etc. Table 10-6 summarizes communication requirements for excepted and fissile-exempt Type A packages. For excepted quantities, communications are limited, unless it qualifies as a hazardous substance (i.e., the quantity is above the RQ limit). When an RQ is shipped as an excepted quantity, it is generally a special form and must have shipping papers like that of a Type A package. When a shipping paper is required for a shipment, Type A and any RQ shipment, the consignee must retain a copy of the shipping papers for 375 days after the material is accepted by the initial carrier, but three (3) years if the hazardous material is hazardous waste. Most individuals will use a shipment quality assurance checklist from the 88 ABW/EM or equivalent.

#### d. RAM Receipt.

(1) General. Organizations receiving NRC-licensed RAM must have written procedures for receiving and opening packages [10 CFR 20.1906(e)]. Appendix B, List B-2 provides a procedure for opening that packages that can be modified by organizations for their own use. Whenever NRC-licensed RAM is received by an organization, record of the receipt must be retained for three (3) years following transfer or disposal of the material (10 CFR 30.51 and 40.61).

(2) Survey Measurements. Packages that are received with DOT White I, Yellow II, and Yellow III labels must be surveyed for external contamination upon receipt, unless they contain only radioactive material in gaseous or special form [10 CFR 20.1906(b)(1)]. Labeled packages must also be surveyed for external radiation levels, unless they are less than or equal to Type A quantities [10 CFR 20.1906(b)(2)]. As well, any package regardless if it contains a DOT label or not must be monitored for external radiation levels and contamination if there is evidence of package degradation or the package is clearly damaged. Surveys must be accomplished as soon as practical, but not later than three (3) hours after receipt if during normal business hours.

(3) DOT Exceedence. As noted in the example procedure for opening packages (Appendix B, List B-2), the AF RIC must be notified if DOT radiation and/or contamination levels are exceeded. The RIC will then notify the NRC, as required by 10 CFR 1906(d).

TABLE 10-6. Communication Requirements Summary for Class 7 (radioactive)  
Material Excepted and Fissile-Excepted Packages (49 CFR, 1 Oct 04).

Quantity	Shipping Paperwork	Exterior of Inner Package	Package Exterior
Excepted-Instrument or Articles (< RQ)	None	None	Marking: "UN2911"
Excepted-Instruments or Articles (> RQ)	Description: shipping name and ID# (Radioactive material, excepted package-instrument or articles, Class 7, UN2911, RQ), quantity of radioactive material, DOT exemptions, description of physical and chemical form (if normal form), name and address of consignee or cosigner, shipper's certification, emergency response phone number.		
Limited Quantity (< RQ)	None	Marking: "Radioactive" (or on package exterior)	Marking: "UN2910"
Limited Quantity (> RQ)	Description: shipping name and ID# (Radioactive material, excepted package-instrument or articles, Class 7, UN2910, RQ), quantity of RAM, DOT exemptions, "Limited Quantity," description of physical and chemical form (if not special form), name and address of consignee or cosigner, shipper's certification, emergency response phone number.		
Manufactured Article (< RQ)	None	Marking: "Radioactive" (or on package exterior)	Marking "UN2909"
Type A Fissile-Excepted (non-bulk)	Description: shipping name and ID# (Radioactive material, Type A, Class 7, UN2915 or 3332, RQ), quantity of RAM, DOT exemptions, description of physical and chemical form (if not special form), package specification (DOT 7A TYPE A, USA), label (& TI), name and address of consignee or cosigner, shipper's certification, and emergency response information and phone number.		<u>Markings:</u> "Shipping name and ID Number, RQ (if hazardous), exemptions, cosignor or consignee's name & address, Type A, mass (if > 50 kg), USA (if for export) <u>Label:</u> "White I or Yellow (II/III, w/ TI)" <u>Placards:</u> (carrier responsibility)

## 11. RAM Storage and Use Area Surveys.

a. General. Survey of RAM storage and use areas is one of the important tasks that are accomplished by BES. While annual surveys must be accomplished in these areas to verify adherence to annual radiation exposure limits, for some storage and use areas, the annual survey may not include measurements, but rather verification that current operating conditions are the same as those that existed during the initial survey.

b. Instrument Selection. The guidance in Table 6-19 should be used in selection of instrumentation if measurements are to be conducted. Per the table, the Victoreen 451B/450, Eberline RO-20, or equivalent are listed as optimal instruments for these types of surveys. However, the ADM-300 with its internal G-M and other listed instruments will provide acceptable results. If the survey areas have neutron fields in addition to photons, it is appropriate to use a neutron measurement instrument as well for survey work. If BES does not possess a neutron instrument, calculations can be performed to assess compliance with exposure limit standards or loaner instrument can be used.

c. Measurement Surveys.

(1) Survey Purpose. Prior to conducting measurement surveys, it is important to establish the purpose of the survey. For most RAM storage and use areas, the primary purpose is to demonstrate or evaluate compliance with occupational and general public radiation exposure standards. Inherent with this is application of the ALARA principle.

(2) Survey Locations. With the survey purpose in mind, survey locations should be chosen based on determining whether an area should be restricted based on the potential for radiation exposure in excess of 2 mrem in any one (1) hour and 100 mrem in a year for members of the public and those occupied by workers in vicinity of the storage/use area and also in adjacent rooms.

(3) Battery and Check Source Response, and Calibration. Appropriate instrument battery checks and verification of proper instrument response with a check source are required prior to collection of survey measurements. Verification that the instrument is within its calibration date should be accomplished as well.

(4) Example for Photon-Emitting RAM Storage.

(a) Locations. Figure B-2 contains an example RAM storage area survey for a variety of small sources that are common to BES operations. The inset diagram shows the location of the storage cabinet in the room and other areas in the vicinity of the cabinet. In this example, the cabinet is stored on an exterior wall, with a technician's desk being located in the same room, but the opposite side. Seven locations were selected for measurement. Location #1 is 30 cm from the exterior of the cabinet and location #3 is 30 cm from the exterior wall, directly adjacent from the cabinet. These locations were selected to evaluate proximity locations with respect to the 2 mrem in any one hour criterion. Locations #2 and #4 were selected to evaluate exposure to the technician that works and has a desk in the room. Locations #5 and #6 in the corridor were selected to assess potential exposures to members of the general public or employees that do not work in this work

area, but use the corridor. Location #7 is the closest work station area for an individual in vicinity of the room, but not in the room.

(b) Exposure Evaluation. The net exposure rate for each measurement location is contained in Figure B-2. First, since none of the measurements are in excess of 2 mrem/hr, it is impossible for the criterion of 2 mrem in any one (1) hour to be exceeded. Second, estimated occupational exposure to the technician that has a desk in the room and other technicians that infrequently utilize the room have a maximum of 17.5 mrem in a year (Figure B-2, page 2). For these calculations, it is assumed that the technicians have a 2000 hour work year. The fraction of time that workers spend in specific locations should be conservatively selected and are highly specific to the individual and/or work area. Some individuals evaluating potential exposure may have assigned the maximum accessible exposure rate to a full 2000 hour work year. In this case, the annual estimated dose-equivalent would have been 40 mrem, however, the conclusion would have been the same – the exposure is below acceptable levels for the general public. Lastly, compliance with acceptable exposure limits to the public are made with an overly conservative assumption that an individual could spend 8 hours/day, 365 days/yr, at location #3. In general, overly conservative assumptions of this nature are not necessary, but for this case and many others that exist in the AF, the general public limit is easily met.

(c) ALARA Considerations. ALARA is inherent to the placement of the RAM storage cabinet in this example. First, the cabinet is placed on an exterior wall, where adjacent exposure potential is low because occupancy is not anticipated to be high in a parking lot. Second, it is logical to locate the technician's desk at a location in the room that is far away from the storage cabinet. Both of these considerations are simple, common sense, and have no cost. For this example, beyond these two considerations, no additional efforts to reduce dose-equivalent appear necessary.

(d) Documentation. Survey documentation should contain the basic information that is provided in this example. BES will have unique survey documents to meet their needs that may have more information provided in this example. At a minimum, survey documents should diagram the RAM storage/use area with details on adjacent areas, information on the RAM or radiation-producing devices being used/stored, instruments used for the survey with serial number and calibration specifications, individual(s) conducting the survey, AF permit number (if applicable), and exposure evaluation conclusions (i.e., the area is unrestricted/restricted, meets or does not meet public exposure limits, etc.). If NRC-licensed materials are involved, the survey meter calibration certificate must be retained for three (3) years after the survey, as the survey report itself. While the certificate does not have to be retained with the survey report, it is good practice since calibration documents may not be readily accessible after the meter undergoes another calibration cycle.

(5) Example for Photon and Neutron Emitting RAM Storage Area. Figure 11-1 contains a RAM storage diagram for an equipment storage and workroom. The RAM storage cage contains a Troxler Model 3440 nuclear density gauge and other equipment that requires lock-and-key security. The room is regularly occupied by a technician (desk - location #2) that handles equipment stored in the room and is required to access the storage cage. Other technicians use the room for small meetings at the conference table (location #6) and to access equipment stored in the cage and other cabinets in the room. One technician has a desk located in the adjoining room, directly adjacent to the storage cage. Figure 11-1 contains photon exposure measurements conducted with a suitable

instrument and estimates of total dose-equivalent, based on information in Table 6-17. Troxler gauges contain  $^{137}\text{Cs}$ , a photon emitting source, and an  $^{241}\text{Am:Be}$  neutron source. Table 6-17 contains the fraction of total dose-equivalent that is quantified by photon measurements-only for the Troxler Models 3430 and 3440 gauges at various distances from the device. For the purposes of estimating the total dose equivalent from photons and neutrons, the measured photon exposure rate was divided by 0.60, the lowest fraction listed in Table 6-17 for the Model 3430 gauge.

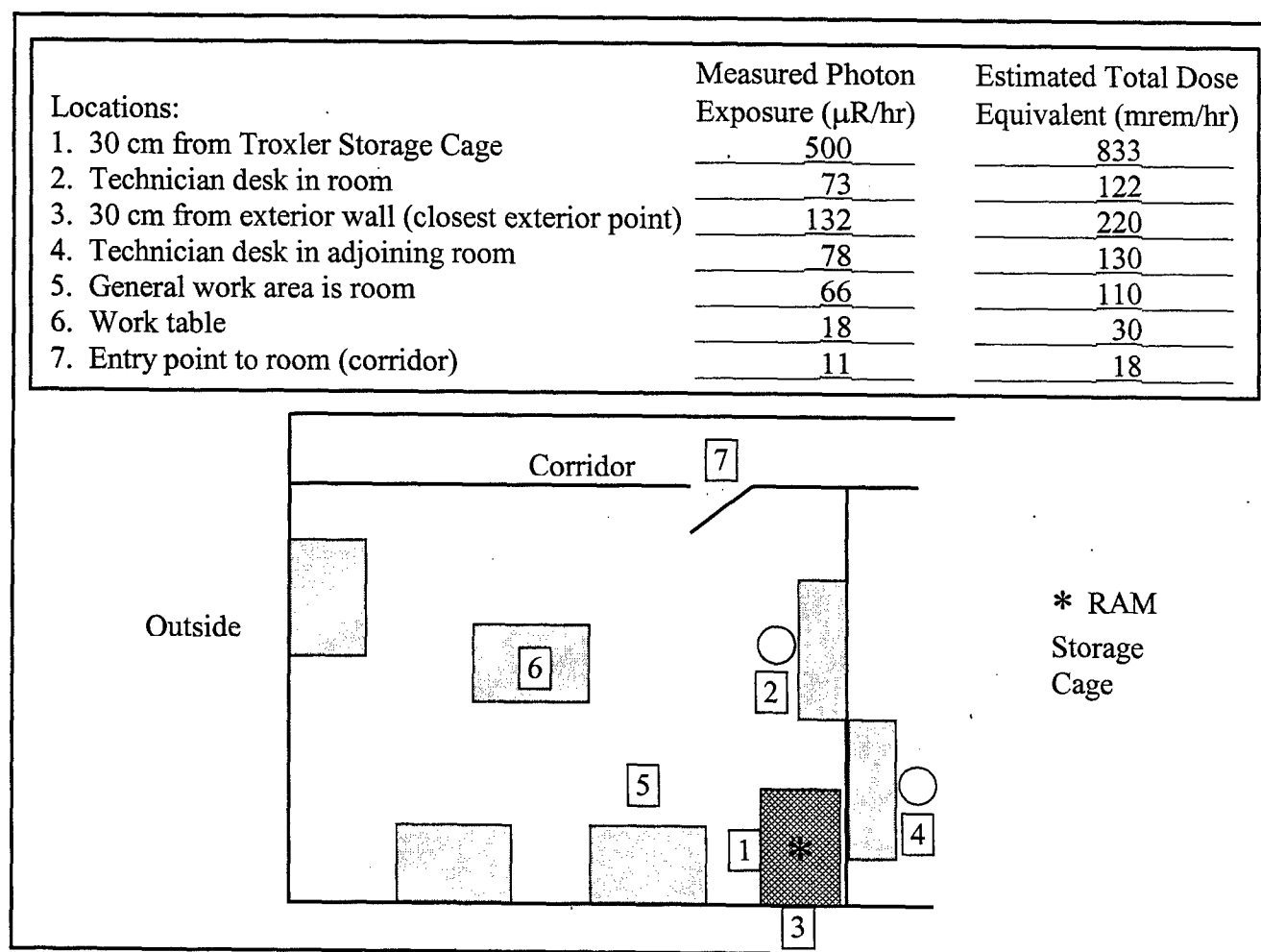


Figure 11-1. RAM Storage Area Diagram.

Table 11-1 contains an exposure summary for workers in the vicinity of the storage cage. The technician working in the room and the technician that uses the desk at location #4 have annual dose equivalent estimates greater than 100 mrem, but none of the accessible locations had exposure rates in excess of 2 mrem/hr. Since estimated exposures are in excess of the public exposure limit, these workers are considered radiation workers and require radiation safety training as specified in 10 CFR 19.12, "Instruction to Workers." If these technicians are not exposed to other occupational sources of radiation (i.e., from using the gauge for survey work or other sources) then they do not require personal dosimetry monitoring (e.g., TLDs) because their projected annual whole-body dose-equivalent is less than 10 % of the annual limit (5000 mrem). General public exposure requires evaluation, but is not provided here.

This example is in contrast to the previous example in good application of ALARA. It is obvious that the storage cage could have been placed in another location in the room or a room that is only infrequently occupied.

TABLE 11-1. Exposure Summary for Workers in Vicinity of RAM Storage Area of Figure 11-1.

Location	Technician Assigned to Room		Other Technicians	
	Fraction of 2000 hr/yr	Dose Equivalent (mrem/yr)	Fraction of 2000 hr/yr	Dose Equivalent (mrem/yr)
1	0.05	42	0.05	42
2	0.5	61		65
4			0.5	3
5	0.05	6	0.05	6
6	0.2	6	0.2	6
Other	0.2	0	0.2	0
Total	1.0	115	1.0	122

## 12. Medical/Diagnostic X-Ray Scatter Surveys.

a. General. X-ray scatter surveys in medical and dental x-ray suites are common radiation protection tasks accomplished by BES. Like other survey measurements, they are only required as a baseline and when there are changes in the operation: installation or modification to the x-ray machines being used, changes in the building structure that affect shielding, or significant changes in the workload. While scatter surveys are an important part of a radiation protection program for x-ray suites, it is important not to neglect other parts of the program: use and evaluation of leaded protective aprons and gloves, entrance skin exposure (ESE) evaluations, and review of the quality control program. AFI 48-148 provides details on these requirements. In general, BES should evaluate all aspects of the program on an annual basis.

b. Initial Acceptance of Diagnostic X-Ray Equipment. All diagnostic x-ray equipment manufactured in or sold in the U.S. must meet performance requirements of 21 CFR 1020. It is AF policy that all new procurements are certified to meet these requirements. Normally a medical equipment repair center (MERC) technician performs or oversees a manufacturer's installation and verifies compliance with the performance requirements.

c. Facility Design. Facilities that are used for diagnostic x-ray should be designed with ALARA in mind and compliance with occupational and general public limits. When new facilities are being designed or significant modification is planned on an existing facility, BES should ensure that adequate radiation safety features are incorporated. Design should consider the following features:

- (1) shielding in the walls and operator booth for the primary and secondary (scatter) beams,
- (2) leaded glass shielding in the operator booth to allow the operator protection and the ability to observe the patient during procedures,
- (3) shielding in doors and around other entry points,
- (4) means for preventing unauthorized entry to the exposure room during exposures (often accomplished by placing the operator's booth near the main entrance,
- (5) the occupancy of adjacent rooms with radiation exposure workload factors,
- (6) consideration for shielding of ceiling and floors to protect areas above and below of the x-ray room,
- (7) shielding for film pass-through and storage boxes to maintain primary shielding and limit film fogging,
- (8) appropriate warning signs indicating the presence of x-rays and reminding patients that may be pregnant to notify the operator prior to exposure so that an evaluation can be made of the necessity of the study, and
- (9) storage for protective devices.

NCRP Report No. 147, "Structural Shielding Design for Medical X-Ray Imaging Facilities," should be used as a guide for shielding design of new and modified facilities. AFIOH/SDR consults on shielding design of medical facilities.

d. Measurements.

(1) Direct Beam Measurements. The output of all medical x-ray machines must be measured annually by MERC or BMET personnel and every four (4) years for dental x-ray. The purpose of direct beam measurements is to determine proper operation of the equipment, assess beam quality, and dose reconstruction. All of these measurements are for the purpose of radiation protection to the patient. These measurements require special instruments that are designed for high exposure rates that are not normally possessed by BES. If dose reconstruction measurements must be conducted in the direct beam, AFIOH/SDR or your regional medical physics consultant should be contacted for guidance. For these cases, specialized instruments and/or TLDs may be recommended for use. If TLDs are planned for use, AFIOH/SDR should be consulted to arrange for non-routine processing, if necessary.

(2) Scatter and Shielded-Direct Beam Measurements. Scatter and shielded-direct beam measurements are conducted to protect workers, other patients, and members of the public from unnecessary radiation exposure. Measurements can be conducted with portable survey instruments possessed by BES or with passive TLDs. The advantage of using TLDs are that calculations with the number of procedures conducted during a specified period, x-ray equipment beam current, and operating potential are not necessary; the integrated exposure only needs to be extrapolated to an annual exposure. The disadvantage is that there are practical limits to the number of measurement locations, whereas for portable instruments a significant number of measurements can be conducted, with selection of areas refined, based on previous measurements. Portable instruments also allow evaluation of leakage through voids in shielding (i.e., utility conduits, vents), the junction of different shielding types (i.e., wall/glass interface, door/wall interfaces, etc.).

(3) Room Layout and Measurement Locations. Figure 12-1 contains a generalized diagram of an x-ray suite. In the example, the machine is located in the center of the room, with the primary beam directed at the patient's location in front of the wall on the right side of the diagram. In this example, the diagram illustrates a chest x-ray exposure geometry, but could be set-up as well to perform vertical exposures where patients are located on a table. The operator's position is shown by location #1, while location #2 is a film pass-through. Locations #3 - #6 are walls. All of these locations should be measured, with particular interest in location #5, that will have shielded-direct and scattered radiations. If locations above and below the x-ray suite are occupied by individuals, measurements should be accomplished. Usually measurements are collected about three (3) feet above the floor levels, since this level is mid-torso for most individuals in standing or sitting positions. Like other measurements collected in RAM storage and use areas, generally measurements collected for radiation fields penetrating surfaces (like walls) should be 30 cm from the surface.

(4) Exposure Parameters. When conducting measurements with portable instruments, it is necessary to scale the measurement at one location from one procedure to an annual exposure that standards are based. X-ray suites should have established x-ray instrument settings for the



diagnostic exams accomplished. The parameters of interest are the tube potential settings: kVp and the integrated current (current \* time), which is normally expressed as mA's. After measurements are conducted, the measured radiation exposure from one procedure can be scaled to that of a year based on the estimated number of examinations of that type conducted. For fluoroscopic x-ray examinations, there is a greater degree of uncertainty in scatter radiation exposure rates, because exposure duration is controlled by the individual operator.

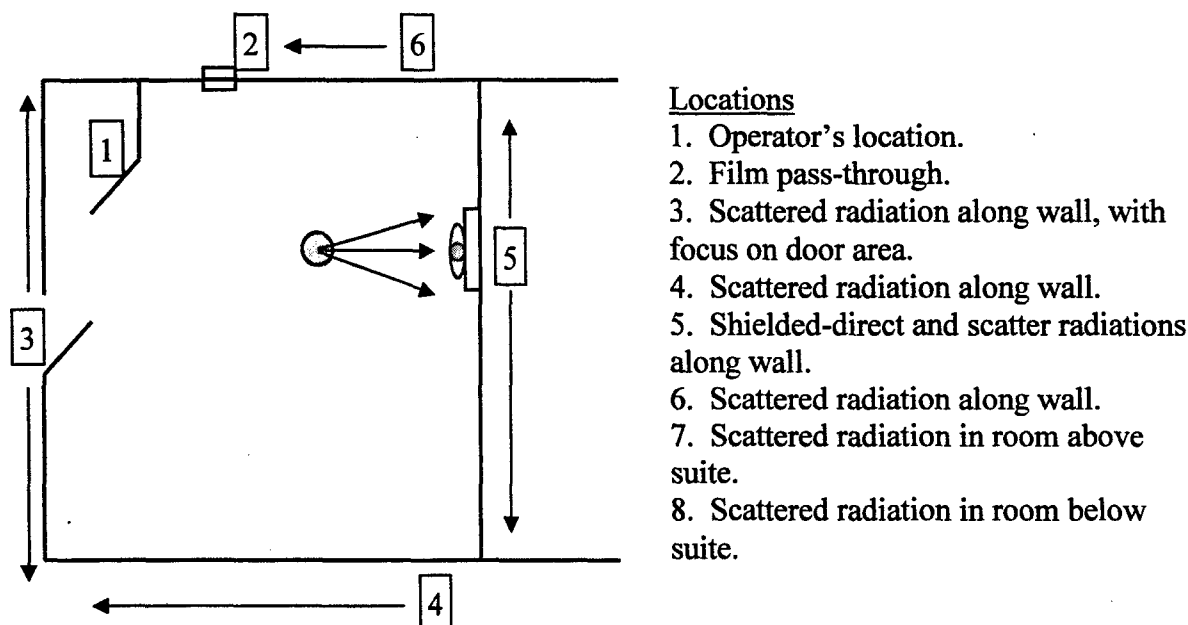


Figure 12-1. Generalized Diagram of Medical X-Ray Suite.

(5) Instrument Selection and Mode of Operation. Section 6 describes various ionizing radiation detection instruments and proper use. Table 6-19 is a radiation detection instrument selection guide. For measurement of diagnostic x-rays, the table lists a number of ion chambers with good response to low-energy photons as optimal for measurements provided the instrument has the capability to integrate exposure. The internal G-M on the ADM-300 is listed as adequate, when used in integrate mode, but does not have as uniform response for lower energy photons as does the example ion chambers. In general, with the exception of some fluoroscopic exposures, most exposure times in diagnostic x-ray are a fraction of a second, making exposure rate measurements impractical since the response time of many instruments are on the order of a few to over eight seconds. While some x-ray machines can be safely operated for a number of seconds, there is risk in damaging the tube, but even a few seconds is inadequate for many instruments to reach a full-scale response in rate mode.

(6) Scattering Medium. For some measurements, like fluoroscopic examinations, it may be possible to collect measurements during actual patient examinations if patient privacy is not a concern. For conventional x-ray procedures, in general, it is not possible to collect adequate measurements since exposure times are typically a fraction of a second. In order to properly

simulate a scattering medium in the beam line, one (1) gallon plastic containers filled with water are normally used as a surrogate. Personnel should never be used as scattering media, unless it is coincident to a routine procedure.

(7) General Safety Considerations for Survey Measurements. It is important that personnel collecting measurements for radiation safety purposes take appropriate measures to conduct the measurements following ALARA. The following considerations should be implemented into measurement protocols.

(a) Remote Exposures. Whenever possible, measurements should be collected in a remote manner. For instruments that integrate exposure, this is easily accomplished. For measurements during fluoroscopic examinations, instruments can be placed in the selected measurement location and be set in integrate mode. For measurements when patient privacy is a concern, this is an acceptable measurement option.

(b) Personal Shielding. When remote measurements are not possible, survey personnel should wear protective aprons and gloves to reduce exposure.

(c) Patient Exposure. It is acceptable to collect survey data during routine radiographic examinations. As discussed earlier, in many cases this will not be practical. If measurements are collected during patient examinations, additional exposures or exposure duration extensions **shall never** be done to provide more complete survey data.

(d) X-ray Technologist Participation. X-ray machines are susceptible to damage from over-heating that may lengthen the survey duration to allow anode cooling. An experienced radiology technician should be present for the measurements to aid in setting up the equipment in modes that are used for patient exposures and to ensure the equipment is not damaged.

(8) Example Measurements for a Basic X-Ray Suite. Table 12-1 contains a table of radiographic procedures for an example x-ray suite with associated x-ray parameters. In the table, example tube potential and integrated current (mA's) per procedure are provided. It is important to note that these are only examples and are provided for the purposes of illustration. These parameters are expected to be different for x-ray suites on your installation. As well, the list provided here is small – most x-rays suites will have an extensive list of procedures. For the purposes of simplifying the survey, only two measurements types will be conducted: one with the x-rays parallel to the floor (simulating a chest x-ray) and the other with the x-ray directed downward to a patient table. Assuming that the x-ray is configured as illustrated in Figure 12-1, measurements along the wall depicted as location #5 will be collected with x-ray parallel to the floor, since in this configuration the exposure rates will be the highest. For other measurement locations, higher exposure rates will be observed with the beam directed downward. While the listed procedures use different tube potential, it is reasonable to simplify the survey by choosing a tube potential that is on the upper end of that used for the listed procedures, since higher x-ray potentials will have greater penetration range in lead shielding. In general, for most diagnostic equipment (non-mammography) 100 keV is a reasonable setting. While tube potentials for most equipment will go as high as 150 kVp, examinations do not generally use potentials this high. For measurements, it is not necessary to set the x-ray equipment on the exposure time used for examinations since measurements can be

correlated to annual integrated current. For example, if a chest x-ray mode is being measured, the maximum mA's of the x-ray machine may be used instead of 30 mA's. As well, if sufficient response with an ion chamber using integrate mode is not received during a single exposure, multiple shots should be accomplished.

TABLE 12-1. Radiographic Procedures and Parameters for Example X-Ray Suite.

Procedure	Integrated Current (mA's) per Procedure	Tube Potential (kVp)	Number of Procedures Annually	Annual Integrated Current (mA's)
Chest	30	80	1,000	30,000
Full Spine	50	90	500	25,000
Abdomen	80	100	600	48,000
			Total	103,000

Table 12-2 contains a summary of measurements and x-ray device settings for this example. Column #1 lists the different measurement locations, with the operating mode listed in parentheses. Since it was desired to have reasonably high integrated exposure on the instrument, multiple x-rays were shot with one (1) second pulse durations and a current of 200 mA. The sixth column (highlighted in gray) represents the integrated exposure measured by the instrument. Since, for this example, a Victoreen Model 451B was used, the integrated exposures are in increments of 0.01 mR (10  $\mu$ R).

For low, integrated-exposure levels, uncertainties in the reported values can be high. For example, at a reported exposure of 0.03 mR, the actual exposure could be in the range of  $> 0.025$  to  $< 0.035$ , for a maximum error of  $\pm 17\%$ . At 0.1, the errors could be as high as  $\pm 50\%$ . For accurate measurements, sufficient integrated exposure is necessary.

TABLE 12-2. Example Measurements for X-Ray Suite, Locations as Illustrated in Figure 12-1 (Tube Potential = 100 kVp).

Location (mode)	Number of X-Ray Shots	Shot Duration (seconds)	Shot Integrated Current (mA's)	Total Integrated Current (mA's)	Max. Total Integrated Exposure (mR)*	Exposure per Integrated Current ( $\mu$ R / mA's)
#1 (down)	10	1	200	2000	0.04	0.020
#2 (down)	10	1	200	2000	0.03	0.015
#3 (down)	10	1	200	2000	0.05	0.025
#4 (down)	20	1	200	4000	0.03	0.010
#5 (chest)	2	1	200	400	0.32	0.80
#5 (down)	20	1	200	4000	0.07	0.018
#6 (down)	10	1	200	2000	0.03	0.015

\* Maximum of potentially many measurements.

The first task surveyors should do when integrated exposure measurements are collected for short pulse durations is to ensure that the peak exposure rate does not exceed the rating of the instrument. For scatter measurements, this is rarely a problem, unless measurements are collected in close proximity to the scatter target and unshielded. For this example, the instrument was subjected to the highest exposure rate at location #5, with chest a chest procedure simulation. In this measurement, the integrated exposure was 0.32 mR, with the total exposure duration being two (2) seconds. Therefore, the exposure rate for this measurement is:

$$\text{Exposure Rate} = \frac{\text{Exposure}}{\text{Time}} = \frac{0.32 \text{ mR}}{2 \text{ s}} * \frac{3600 \text{ s}}{\text{hr}} = 0.576 \frac{\text{R}}{\text{hr}},$$

where the exposure rate is below the maximum for this instrument, 50 R/hr (Table 6-3).

(9) Application of Measurements to Standard. Once measurements have been conducted, estimated annual exposures should be calculated based on expected occupancy for specific locations and conservative estimates of the annual workload for the x-ray suite. NRCR Report No. 147 (NRCR 2004) contains occupancy factors for non-occupationally exposed persons for x-ray shielding design when other occupancy data is not available.

TABLE 12-3. Occupancy Factors for Non-Occupationally Exposed Persons (NCRP 2004).

Occupancy Factor	Area
1	Administrative or clerical offices; laboratories, pharmacies, and other work areas fully occupied by an individual; receptionist areas, attended waiting rooms, children's indoor play areas, adjacent x-ray rooms, film reading areas, nurse's stations, x-ray control rooms
0.5	Rooms used for patient examinations and treatments
0.2	Corridors, patient rooms, employee lounges, staff rest rooms
0.125	Corridor doors
0.05	Public toilets, unattended vending areas, storage rooms, outdoor areas with seating, unattended waiting rooms, patient holding areas
0.025	Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking lots, vehicular drop areas (unattended), attics, stairways, unattended elevators, janitor's closets

Table 12-4 contains a summary of estimated annual exposures based on the measurements, occupancy, and annual workload. For each location, the use is provided and the occupancy factor from Table 12-3. Annual exposure is the product of occupancy factor, exposure per integrated current, and the annual integrated current. An example calculation is shown for location #1:

$$\begin{aligned}\text{Annual Exposure} &= \text{Occupancy} * \frac{\text{Exposure}}{\text{Integrate Current}} * \text{Annual Integrated Current} \\ &= 1 * 0.020 \frac{\mu\text{R}}{\text{mAs}} * 103,000 \text{ mAs} * \frac{\text{mR}}{1000 \mu\text{R}} = 2.1 \text{ mR}.\end{aligned}$$

TABLE 12-4. Estimated Annual Exposure for Locations of Example in Table 12-2.

Location	Use	Occupancy Factor	Exposure per Integrated Current ( $\mu\text{R} / \text{mA's}$ )	Annual Integrated Current (mA's)	Annual Exposure (mR)
#1	Operator Station	1	0.020	103,000	2.1
#2	Film Pass Through	1	0.015	103,000	1.5
#3	Corridor	0.2	0.025	103,000	0.52
#4	Offices	1	0.010	103,000	1.0
#5	Storage Room	0.05	0.80	30,000	1.5
#6	Film Room	1	0.015	103,000	1.5

For all locations, but #5, it was assumed that the annual integrated current was 103,000 mA's, as listed in Table 12-1. For location #5, the exposure from procedures where the beam was directed down were neglected since they would contribute very little to total exposure when compared to the exposure provided by chest x-rays. In summary, for all locations measured, calculated annual exposures were significantly less than 100 mrem, the annual limit for members of the general public.

The only location that has the potential for high exposures is #5 because the chest x-ray bucky is located on the wall opposed to this location. While for this example it is assumed that the room is used for storage, future changes in its use and an increase in workload could create more concern about exposures.

One important observation for this set of measurements is that measured exposure was very low when the beam was directed downward and exposure was significantly higher when the beam was oriented simulating a chest x-ray. This is common to most x-ray suites: chest x-ray exposures will provide the greatest exposures on the exterior of an x-ray room, while exposure rates from downward-directed x-rays may be minimal or even un-measurable.

### 13. Identification of Unknown Emitters.

a. Purpose and Scope. BES during routine operations and in planning for accident/incident scenarios may have to identify unknown RAM. With recent concern over the use of weapons of mass destruction, there is increased preparedness for BES responding to potential nuclear device or dirty bomb dispersals of RAM. In line with this concern, BES flights were allocated  $\gamma$ -spectroscopy equipment to aid in the identification of unknown RAM. The probability of its use in these scenarios is very low, as such, BES will have greater use of this equipment in training scenarios and in identification of unknown RAM that is likely related to AF activities. Therefore, this section will concentrate on these two separate areas and discuss additional considerations.

b. Radioisotopes. The proper identification of unknown radionuclides under accident/incident or routine scenarios should be based on the availability of the isotope and its commonality of use. Table 13-1 contains a list of isotopes that are suspect radioisotopes for dirty bombs or nuclear

TABLE 13-1. Isotopes Considered for Dirty Bomb, Nuclear Device, and Other.

Radioisotope	Radiations			Use	Radioisotope	Radiations			Use
	$\alpha$	$\beta/e^-$	$\gamma/x$			$\alpha$	$\beta/e^-$	$\gamma/x$	
Isotopes Common to Industrial/Medical/Research Use									
P-32		HE	*	Resear.	DU	X	HE	LE	Many
Co-60		LE	XX	Many	Ra-226 (& daughters)	X	HE	XX	Many
Sr-90/Y-90		HE	*	Many					
Mo-99		HE	X	Medical	Pu-238	X	VLE	L LE	Indust.
I-125		VLE	X	Medical	Pu-239+240 (plus Pu:Be)	X	VLE	L LE	Indust.
I-131		ME	X	Medical					
Cs-137		ME	X	Many	Am-241 (plus Am:Be)	X	VLE	LE	Indust.
Ir-192		ME	XX	Many					
Additional Isotopes Common to AF Operations (of significant quantity)									
Highly Enriched Uranium	X	ME L	LE L	Nuclear Weap.	Thorium (& daughters)	X	ME HE	XX	Many
Less Common Industrial Isotopes									
Se-75		VLE	XX	Radiog.	Cf-252 (spontaneous fission)	X	ME	X	Many
Yb-169		LE	X	Radiog.					
Tm-170		HE	L	Radiog.					

VLE = very low energy (assumed to be undetectable with portable survey instruments)

LE = low energy

L = low frequency emissions

ME = medium energy

X = significant photon emissions

HE = High Energy

XX = high frequency photon emissions

\* Bremsstrahlung x-rays could be present

devices based on their availability and commonality of use. The first portion of the table contains isotopes that are commonly used world-wide in industry, medicine, and research, and in sufficient quantities. From the list, many of the isotopes are also common to routine AF operations, for example:  $^{60}\text{Co}$ ,  $^{90}\text{Sr}/^{90}\text{Y}$ ,  $^{131}\text{I}$ ,  $^{137}\text{Cs}$ , DU,  $^{226}\text{Ra}$ ,  $^{239+240}\text{Pu}$ , and  $^{241}\text{Am}$ . Highly enriched uranium (HEU) is used in nuclear weapons, but in quantity is not common to industrial, medical, or research. Thorium is common in AF operations, but is not considered as useful as a dirty bomb material because of its low specific activity. Some details on radioactive emissions from the first two sections of Table 13-1 are also in Tables 3-4 and 3-5. The last section lists some isotopes that are used in industry, but are not as common as those listed in the first section. For listed isotopes, the table provides a simplified summary of radioactive emissions:  $\alpha$ -,  $\beta$ /e-, and photons ( $\gamma$ /x-ray), with detail on energy and frequency of emission. This information is useful to field personnel in the initially screening of potential contaminants based on field data (i.e., the contaminant in the field has emissions of  $\alpha$ - and  $\beta$ -particles and significant  $\gamma$ -radiation exposure levels, or perhaps it has  $\alpha$ -particle emissions with little or no  $\gamma$ -radiation, etc.). Suspected contaminants can be easily screened with information from basic portable survey instruments, like the ADM-300, and more precisely identified by additional information from  $\gamma$ -spectroscopy, unless the RAM does not emit photons. Most unknown AF contaminants can be identified with information from portable instruments.

Table 13-2 contains a summary listing of the radiation emissions from highly enriched uranium (HEU) based on environmental sampling at a nuclear weapons maintenance waste site. The uranium mass and activity fraction assumptions are annotated in the title. HEU has a significantly different composition of radiation emissions as compared to the example emissions from moderately-depleted uranium in Table 6-1. First, DU has about 1.5  $\beta$ -particles per  $\alpha$ -particle emission, while HEU has one (1) for every 30  $\alpha$ -particle emissions. The most important potential RAM at nuclear weapons sites are HEU, DU, and WGP. Table 13-3 contains an example of WGP based on mass and activity concentrations in 1958, when the material was produced, and 2005. From the table, the majority of mass is from  $^{239+240}\text{Pu}$ , while at production, the greatest radiological activity is from  $^{241}\text{Pu}$ , due to

TABLE 13-2. Radiation Emissions from Highly-Enriched Uranium (Includes Short-Lived Daughters) [Uranium Activity Fraction:  $^{234}\text{U} - 0.965$ ,  $^{235}\text{U} - 0.035$ ,  $^{238}\text{U} - 0.0004$ ], [Uranium Mass Fraction:  $^{235}\text{U} - 0.923$ ,  $^{238}\text{U} - 0.068$ ,  $^{234}\text{U} - 0.009$ ] (Rademacher 2002).

$\alpha$ -Emissions		$\beta$ -Emissions		Photon Emissions	
Energy (MeV)	Frequency	Energy (MeV)	Frequency	Energy (MeV)	Frequency
4.78	69 %	0.287	1.7 %	0.1857 ( $\gamma$ )	2.0 %
4.72	27.5 %	0.304	1.2 %	0.0256 ( $\gamma$ )	0.5 %
4.40	2.0 %	0.05	0.5 %	0.143 ( $\gamma$ )	0.4 %
4.21	0.3 %	Others	< 0.1 %	0.0926 ( $\gamma$ )	0.3 %
Others	1.2 %	Blank		0.0842 ( $\gamma$ )	0.2 %
Blank				Th, U, & Pa x-rays	> 1 %

its relatively short half-life. Over long periods of time, the  $^{241}\text{Pu}$  is diminished through radioactive decay to  $^{241}\text{Am}$ . In this example, after 47 years of decay, the  $^{241}\text{Am}$  undergoes in-growth from a negligible contribution to an activity of almost 20 % of that of the  $\alpha$ -emitting plutonium isotopes.

TABLE 13-3. Isotopic Composition of WGP, Based on Los Alamos National Laboratory Estimates and Soil Analyses from AF Restoration Project (Rademacher 2001).

Isotope (Decay Mode)	Radiological Half-Life (yr)	Estimate in 1958		Activity Fraction Estimate in 2005
		Mass Fraction	Activity Fraction	
Pu-238 ( $\alpha$ )	87.74	0.000099	0.003	0.010
Pu-239 ( $\alpha$ )	24,110	0.937	0.103	0.474
Pu-240 ( $\alpha$ )	6,560	0.056	0.023	0.104
Pu-241 ( $\beta$ )	14.35	0.0047	0.871	0.413
Pu-242 ( $\alpha$ )	376,000	negligible	negligible	negligible
Am-241 ( $\alpha$ )	432	negligible	negligible	0.189*

\*  $^{241}\text{Am}$  activity fraction is not included with Pu isotopes. The number listed is its ratio to the sum of Pu  $\alpha$ -particle emitters.

Table 13-4 provides a summary of the radiation emissions from the WGP of Table 13-3. From the table, it is apparent that the only  $\beta$ -particle emission is of very-low energy, that is undetectable with portable survey instruments, and photon emissions have low emission frequency and are of low energy. Therefore, as an environmental contaminant, WGP, is very difficult to quantify with portable survey instruments as compared to other contaminants like DU, HEU,  $^{226}\text{Ra}$ , and many common  $\gamma$ -emitting radionuclides used in the AF. The 0.06 MeV photon is from  $^{241}\text{Am}$ , which is useful for quantifying WGP in the environment with portable NaI(Tl) systems, like the FIDLER (see Section 6e3d) ), except that the relationship between the  $^{241}\text{Am}$  and  $^{239+240}\text{Pu}$  would not be known in accident, incident, or dirty bomb scenarios by first responders. This information would have to come from classified sources or determined by more detailed analyses.

TABLE 13-4. Radiation Emissions from WGP, Isotopic Mixture of Table 13-3 (2005) [Normalized to Total  $\alpha$ -Particle Activity].

$\alpha$ -Emissions		$\beta$ -Emissions		Photon Emissions	
Energy (MeV)	Frequency	Energy (MeV)	Frequency	Energy (MeV)	Frequency
5.16	50 %	0.005	59 %	0.060 ( $\gamma$ )	5.7 %
5.49	13 %	Blank	Blank	0.014 (x)	10.4 %
5.17	11 %			Blank	
5.14	10 %				
5.11	8 %				
Others	8 %				



c. Unknowns in Accident, Incidents, and Dirty Bomb Scenarios.

(1) BES Responsibility. BES will be the primary radiological health and safety advisor to a military on-scene commander in the event of a military response to a radiological accident, incident, or dirty bomb scenario. To accomplish this role, BES has radiation detection equipment, air sampling equipment, and computer modeling capabilities to measure and project airborne and ground deposition patterns of contamination. With this information, BES aids on-scene commanders in setting controlled areas, and provides recommendations for respiratory protection and protective clothing, and surveillance activities for personnel in contamination control. Within this role, identification of unknown radiological contaminants is a function that BES performs, with recent addition of  $\gamma$ -spectroscopy equipment. While identification of unknown radiological contaminants is an important BES function, BES must keep in mind that many of the protective actions that they recommend in the initial stages of an accident response may be made without identification of the contaminant. For example, in the initial stages of an accident, BES will conduct air sampling and perform ground monitoring to determine:

- (a) if there is airborne or ground-deposited radiological contamination, and
- (b) whether or not the contamination emits  $\alpha$ -,  $\beta$ -, and/or photon radiations,
- (c) intensity of the contamination, and
- (d) external exposure rates.

If airborne contamination exists, respiratory protection will be recommended for use, regardless of the isotope involved. As well, if external exposure rates from ground-deposited RAM are high due to a strong  $\gamma$ - and/or  $\beta$ -emitting radionuclide, the time duration that personnel spend in contamination zones will be restricted based on these exposure rates, but generally not based on the contaminant type. Identification of the contaminant may serve some limited function in the initial stages of an accident. First, if some individuals have already suffered an internal burden of radiological material (likely from inhalation), identification of the contaminant is necessary in determining whether medical intervention may be advised, like the administration of chelating agents to aid excretion. Second, among the isotopes listed in Table 13-1, if radioiodines (i.e.,  $^{125}\text{I}$  or  $^{131}\text{I}$ ) are present, air purifying respirators should be fitted with combination filters that contain activated charcoal and particulate filters. Third, administration of KI may be recommended for members of the public and personnel to protect from future uptakes if radioiodine are involved in a release. In summary, while identification of the radiological contaminant in the initial stages of an accident may serve a limited function, it is important that BES provides adequate attention to primary monitoring activities listed above.

(2) Sample Analysis. There is the potential for a significant amount of radiological information at an accident, incident, or dirty bomb site to discern radionuclide identity. The following is a list of potential sources with discussion.

(a) Field Team Entries to Contaminated Ground Areas. After the release of RAM in one of these scenarios, there is potential that access to ground areas with the most significant levels of

contamination may be restricted until the area can be cleared by explosives ordnance disposal (EOD) personnel or other hazards that may exist. However, if entry is allowed by teams, evaluation of ground contamination is a useful method of radionuclide identification. While external exposure rates are of key importance to personnel protection, evaluation of  $\alpha$ - and  $\beta$ -emissions, and in-situ  $\gamma$ -spectroscopy of contaminated ground surfaces will be useful. Collection of contaminated soils from the contamination zone will allow more detailed  $\gamma$ -spectroscopy in a more controlled environment (i.e. field laboratory) and reduce radiation exposure and other risks to field teams.

(b) Contamination. Contamination is likely to exist on the surface of equipment, personnel, and casualties when exiting contaminated areas. Measurement of contamination on the surface and swipe samples can be useful in unknown identification. One of the most important set of measurements is for the existence of  $\alpha$ - and  $\beta$ -contamination. All of the contaminants listed in Table 13-1 have  $\alpha$ - and  $\beta$ -emissions or  $\beta$ -emissions alone. The distinction between the two cases can reduce the list of suspected contaminants in half.

(c) Air Samples. Air samples are important in force protection. Some information from air samples may be useful in identification of unknown radionuclides. The information gained from air samples is similar to that obtained from samples of contamination, except that measurement of relative ratios between  $\alpha$ - and  $\beta$ -contamination is plagued with less certainty in the detection efficiencies due to unknown self-absorption, unless the contamination is on filter swipes.  $\gamma$ -spectroscopy analysis with field instruments like the SAM-935 is difficult for air or swipe samples if the contamination levels are low because background radiations will dominate the spectra.

(3) Identification of Unknowns by Integration of Various Data Sources. Table 13-5 contains a listing of various measurements from an airborne release of RAM from an explosive event, based on measurements from field teams, contamination, and air samples. The table lists the relative importance of individual measurements with respect to identification of unknown radionuclides. It is important to note that while some measurement information may not be important to unknown identification, it may serve some other important radiological safety need.

(a) Unknown Identification, Example #1. Table 13-6 contains measurement information for the first example of unknown identification from field data. From  $\alpha$ - and  $\beta$ -contamination measurements by field teams in the contaminated area, it is apparent that the unknown RAM emits  $\beta$ -particles, but does not have  $\alpha$ -particle emissions. This is reinforced by analysis of air filter samples.  $\gamma$ -radiation exposure measurements in the contamination zone with the ADM-300 internal G-M detector indicate that there is significant amount of material deposited on the soil to provide an exposure rate of 30 mR/hr, with the  $\beta$ -shield closed. With the  $\beta$ -shield open, the instrument's response almost doubles which is attributed to  $\beta$ -radiation. Therefore, up to this point in the evaluation, of the isotopes listed in Table 13-1, all  $\alpha$ -particle emitters can be excluded as well as very, low-energy  $\beta$ -particle emitters ( $^{125}\text{I}$  and  $^{75}\text{Se}$ ). As well, since the material is deposited on the ground, the potential for Bremstrahlung x-ray should be small and incapable of producing the external exposure rates observed from pure  $\beta$ -particle emitters ( $^{32}\text{P}$  and  $^{90}\text{Sr}/^{90}\text{Y}$ ). Thus, among the isotopes common to industry, medical, and research, the remaining ones are:  $^{60}\text{Co}$ ,  $^{99}\text{Mo}$ ,  $^{131}\text{I}$ ,  $^{137}\text{Cs}$ ,

TABLE 13-5. Potential Radiological Measurements and Importance to Identification of Unknown Radiological Emitters in Field Conditions.

Measurement	Field Team Entries in Contaminated Areas	Contamination on Equipment, Personnel, and Casualties	Air Samples
$\gamma$ -Radiation Exposure	Moderate	Limited, no photon energy information	Limited, no photon energy information
$\gamma$ -Spectroscopy	High	Low to Medium, dependent on amount of material*	Low to Medium, dependent on amount of material*
$\alpha$ -Contamination	Moderate	Moderate	Moderate
$\beta$ -Contamination	Moderate	Moderate	Moderate
$\gamma$ -Spectroscopy Analysis of Sample	High	Moderate	NA
Relative $\alpha$ -to $\beta$ -Contamination Levels Measure on Surface	Low, due to uncertainty in detection efficiency	Low, due to uncertainty in detection efficiency	Moderate to High
Swipe $\alpha$ - to $\beta$ -Contamination Levels	Moderate	Moderate	NA

\* Field  $\gamma$ -spectroscopy by BES spectroscopy equipment may have high uncertainties. High-resolution  $\gamma$ -spectroscopy afforded by specialized teams, like AFRAT, will provide better analysis.

TABLE 13-6. Radiological Measurement Data from Unknown Identification, Example #1.

Measurement	Source	Data
$\gamma$ -Radiation Exposure	Field Team Entry ADM-300 Internal G-M $\beta$ -Shield Closed	Maximum – 30 mR/hr
$\alpha$ -Contamination	Field Team Entry ADM-300 AP-100	None
	Air Sample ADM-300 AP-100	Approximately equal to background.
$\beta$ -Contamination	Field Team Entry ADM-300 Internal G-M $\beta$ -Shield Open	Maximum – 70 mR/hr Net = 40 mR/hr*
	Air Sample ADM-300 BP-100	300 cpm (t = 3 hr post, no filter) 110 cpm (t = 3 hr post, 3 sheets paper) Background – 20 cpm

\* Net of 40 mR/hr is from potential  $\beta$ -radiation contribution, but is meaningless in terms of exposure (mR/hr) units.

and  $^{192}\text{Ir}$ . Additional measurements were conducted on the air sample filter with varying thicknesses of paper absorber. With three (3) thicknesses a paper inserted between the air filter sample and the

ADM-300 BP-100 probe, the net exposure rate dropped from 280 to 110 cpm, having an attenuation factor of 0.39. Using Figure 6-9, the attenuation observed closely resembles a medium energy  $\beta$ -particle emitter like  $^{137}\text{Cs}$ . Of the five likely suspects listed, only  $^{131}\text{I}$ ,  $^{137}\text{Cs}$ , and  $^{192}\text{Ir}$  have medium energy  $\beta$ -emissions.  $\gamma$ -spectroscopy analysis of a moderately contaminated wipe or air samples, or soil samples should be useful in discriminating the difference between the three (3) isotopes. Table 3-4 lists some photon emission energies for common isotopes and can be used to aid in interpretation of  $\gamma$ -spectroscopy results.

(b) Unknown Identification, Example #2. Table 13-7 contains measurement information for the second example of unknown identification from field data. From  $\alpha$ - and  $\beta$ -contamination measurements by field teams in the contaminated areas, it is apparent that the unknown RAM emits  $\alpha$ -particles and possibly  $\beta$ -particles, because the response of the ADM-300 internal G-M is about 33 % higher with the  $\beta$ -shield open as compared to closed. However, in comparison of the relative  $\alpha$ - and  $\beta$ -radiation emissions from the air filter sample, it appears that the material does not have detectable  $\beta$ -particle emissions or if they exist, they are of very low-energy. At this point in the review, only isotopes with  $\alpha$ -particle emissions and very, low-energy  $\beta$ -particles, or no  $\beta$ -particle emissions should be considered. This limits the isotopes from Table 13-1 to  $^{238}\text{Pu}$ ,  $^{239+240}\text{Pu}$ , or  $^{241}\text{Am}$ .  $\gamma$ -spectroscopy analysis should be useful in discrimination among the three. If  $^{241}\text{Am}$  is identified in the analysis, it could be pure  $^{241}\text{Am}$  or WGP that contains  $^{241}\text{Am}$ ,  $^{239+240}\text{Pu}$ , and small amounts of  $^{238}\text{Pu}$  (see Table 13-3). From a practical standpoint, protective measures will be the same regardless of which of the three is identified; specific identification will be made from laboratory analysis of contamination after the initial stages of the incident response. For this example, it appeared from the field measurements with the ADM-300 internal G-M that detectable  $\beta$ -radiation existed in the contaminant. If the contaminant is  $^{238}\text{Pu}$ ,  $^{239+240}\text{Pu}$ , or  $^{241}\text{Am}$ , the difference in G-M response with the  $\beta$ -shield open and closed can be attributed to attenuation of low-energy photons by the shield.

TABLE 13-7. Radiological Measurement Data from Unknown Identification, Example #2.

Measurement	Source	Data
$\gamma$ -Radiation Exposure	Field Team Entry ADM-300 Internal G-M $\beta$ -Shield Closed	Maximum – 0.75 mR/hr
$\alpha$ -Contamination	Field Team Entry ADM-300 AP-100	Maximum – 500,000 cpm
	Air Sample ADM-300 AP-100	450 cpm (t = 3 hr post) Background – 20 cpm
$\beta$ -Contamination	Field Team Entry ADM-300 Internal G-M $\beta$ -Shield Open	Maximum – 1.0 mR/hr Net = 0.5 mR/hr
	Air Sample ADM-300 BP-100	Approximately equal to background. (t = 3 hr post)

\* Net of 1 mR/hr is from potential  $\beta$ -radiation contribution, but is meaningless in terms of exposure (mR/hr) units.

(4) Mixtures. While the two examples provided here were depicted to have only one radiological contaminant, it is possible that multiple contaminants may be in a release. In these cases,  $\gamma$ -spectroscopy analysis will be more vital in the identification process. While responders will not know whether or not multiple radiological contaminants are involved in an unknown release, the two examples provided here illustrate how to integrate common radiological field data that will be available during the initial stages of an incident response. If an incident has radiological complexity that is difficult for BES to adequately interpret, AFIOH/SDR should be consulted for assistance. Naturally, if related to an accident/incident response, follow-on specialized teams can provide specific identification.

(5) Field  $\gamma$ -Spectroscopy. Field portable  $\gamma$ -spectroscopy systems are possessed by BES for response to weapons of mass destruction incidents. In the near future, systems like these will be part of BES standard radiological detection instruments for routine operations. Some general guidelines should be considered in making better measurements.

(a) Shielding. Measurements of discrete samples like a soil, air filter, or swipe sample should be evaluated in a shielded environment to reduce the influence of naturally-occurring background radiations from the environment. While heavy, low-background lead shielding may be impractical to transport with response equipment, in-field makeshift shielding with steel can aid measurements.

(b) Background Radiation. When spectra are collected to assess the identity of an unknown, it is important to consider the influence of background radiations. When samples are measured at a fixed location, separate background spectra can be collected. For measurements in contaminated areas, where background spectra cannot be directly related, it is important to account for photons that commonly exist in the environment, as listed in Table 13-8. The photons listed are

TABLE 13-8. Photon Energy and Emission Frequency for Key Environmental Background Radionuclides (Low Emission Frequency Photons Emitted).

Energy (MeV)	Emission Frequency	Isotope	Decay Series	Energy (MeV)	Emission Frequency	Isotope	Decay Series
0.0633	3.8 %	Th-234	U-238	0.583	86 %	Tl-208	Th-232*
0.1857	54 %	U-235	U-235	0.609	47 %	Bi-214	U-238**
0.186	3.6 %	Ra-226	U-238	0.727	12 %	Bi-212	Th-232
0.239	45 %	Pb-212	Th-232	0.860	12 %	Tl-208	Th-232*
0.241	3.9 %	Ra-224	Th-232	0.911	28 %	Ac-228	Th-232
0.242	7.5 %	Pb-214	U-238**	0.969	17 %	Ac-228	Th-232
0.295	19 %	Pb-214	U-238**	1.12	17 %	Bi-214	U-238**
0.338	11 %	Ac-228	Th-232	1.46	11 %	K-40	
0.352	36 %	Pb-214	U-238**	1.76	17 %	Bi-214	U-238**
0.511	22 %	Tl-208	Th-232*	2.61	100 %	Tl-208	Th-232*

\*  $^{208}\text{Tl}$  exist in 36 % abundance to  $^{232}\text{Th}$  decay chain parent; to relate relative photon emission abundance to other  $^{232}\text{Th}$  decay chain daughter listed, multiply the  $^{208}\text{Tl}$  photon emission frequencies by 0.36.

\*\* Daughter radionuclides of  $^{226}\text{Ra}$  (see Figure 6-13 for more detail).

the most abundant in frequency as emitted by  $^{40}\text{K}$ , and the  $^{238}\text{U}$ ,  $^{235}\text{U}$ , and  $^{232}\text{Th}$  decay series. The photons are listed in order of increasing energy, with emission frequency, isotope, and decay series. It is important to note that many of these isotopes are observed in common AF RAM. For example, the 0.0633 keV photon from  $^{234}\text{Th}$  is observed in DU,  $^{226}\text{Ra}$  and its daughters are common to old aircraft components that were painted with self-illuminating radium paint, and MagTh alloys contain the isotopes in the  $^{232}\text{Th}$  decay series.

(c) Characteristics of Spectroscopy Systems and Spectra. Section 6.e.(4) provides some example spectra from common RAM used in the AF, with discussion of characteristics that are common to spectra produced by spectroscopy systems. It is important that individuals using these systems have training on using the system and how to interpret the spectra, with the aid of standard system libraries. Attention should be paid to the potential for misinterpretation of spectral peaks.

(6) Nuclear Weapons Accident Material Mixtures. Historically, most BES personnel have had extensive training on response to nuclear weapons accidents. As discussed earlier in this section, WGP, HEU, and DU are the most important potential RAM that may be released in a fire or high-explosives detonation. Nuclear weapons may contain a combination of these RAM, with precise mass and mass combinations being classified for U.S. systems. For releases with the potential for a combination of these, it is important to understand the practical field detection implications. Figure 13-1 contains specific activities for these three RAM, based on the mixtures already detailed in this report for  $\alpha$ -emitting isotopes. From the table, the example WGP has over

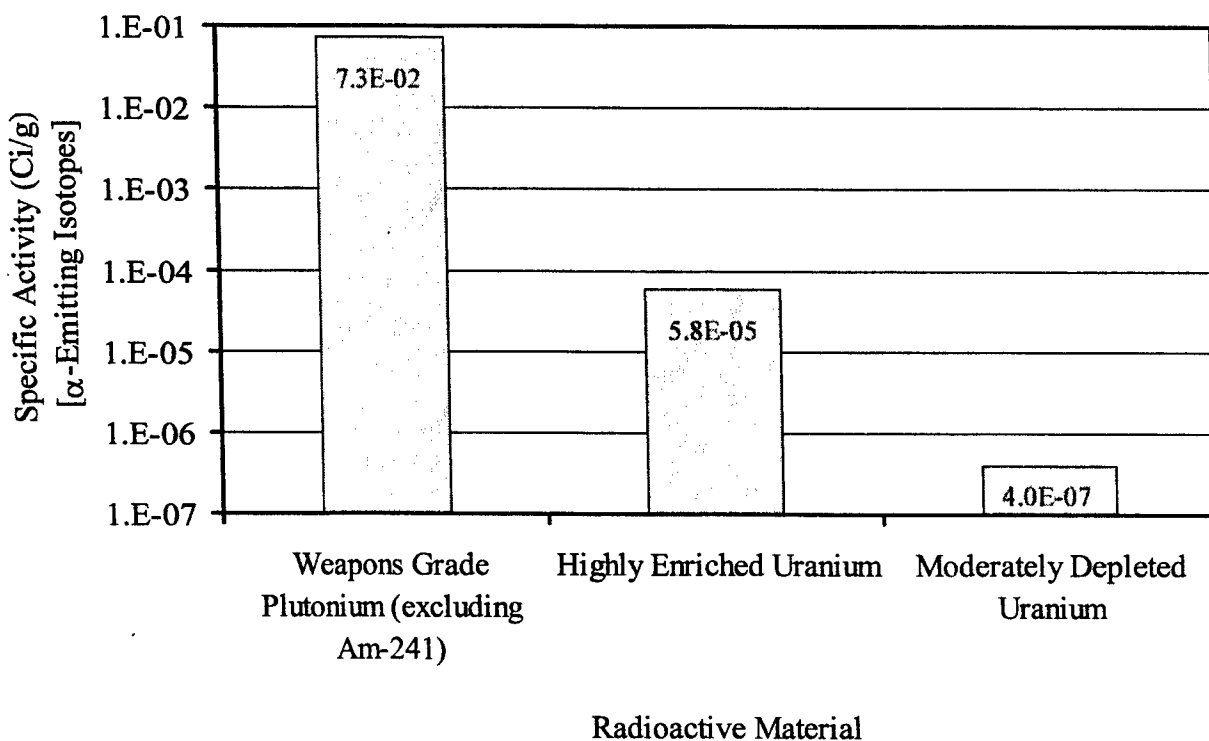


Figure 13-1.  $\alpha$ -Emitting Isotope's Specific Activity for Key Radioactive Materials Used in Nuclear Weapons [WGP (Table 13-3, 2005), HEU (Table 13-2), Moderately Depleted Uranium (Table 6-1)].

three (3) orders of magnitude higher  $\alpha$ -particle activity than an equal mass of the example HEU. In comparison, for the example WGP and DU, on an equal mass basis, there is five (5) orders of magnitude difference. Therefore, if two or more of the RAM are released during an accident, it is likely that the material with the greatest specific activity will greatly mask the other material(s) and take precedence in radiation dose modeling and other protective actions.

d. Unknowns in Routine AF Operations.

(1) General. BES during routine shop visits, in support of aircraft displays, and in assistance to environmental restoration activities on their installations may have to identify unknown RAM. While almost all manufactured RAM today is labeled (with "Caution – Radioactive Material," isotope, and activity, except some exempt items), RAM that may be encountered in these activities may not be labeled. In general, the same considerations provided above should be made when identifying unknown RAM as released in an incident, accident, or dirty bomb scenario, except that the list of potential isotopes is considerable smaller. Table 5-12 contains a list of some of the specifically-permitted RAM used in the AF, while Tables 5-15 and -16 contains information on some of the exempt quantities. Most AF specifically-licensed and exempt RAM are unlikely to require identification because they are labeled and in sealed form. Table 13-9 contains a list of AF RAM with the most potential for existence at environmental restoration sites. While restoration sites may not be inclusive of all unknown RAM that BES will have involvement during routine operations, it is likely most unknowns will be among the RAM listed in the table. Among these,  $^{226}\text{Ra}$ , DU, and  $^{232}\text{Th}$  are most likely.

(2) Assessment Considerations. While the same radiological considerations for the RAM encountered in routine AF operations are similar to that of materials in accidents, incidents, and dirty bomb scenarios, some differences should be noted. For example, in the above scenarios, it is assumed that the release is current, while for unknown identifications scenarios, loose RAM may be dispersed in soil or adsorbed in the surfaces of material because long periods of time may have elapsed since release. Under conditions like these, for  $\alpha$ - and low-energy  $\beta$ -particle-emitting RAM, detection of surface emissions may be highly degraded or not possible due to attenuation. For example, in the case of  $^{226}\text{Ra}$  adsorbed in concrete surfaces from past self-illuminating dial painting operations,  $\beta$ - and  $\gamma$ -radiations will be detectable for in-situ measurements, but  $\alpha$ -emissions may not be detectable. In this type of scenario, it would be improper to discount  $^{226}\text{Ra}$  as the potential contaminant solely due to the absence of  $\alpha$ -particle detections. Similar conclusions can be made for other  $\alpha$ -particle emitters distributed in soils.

(3) Example Quantities and Measurements.

(a)  $^{226}\text{Ra}$ . Table 13-10 contains common characteristics of AF self-illuminating devices with  $^{226}\text{Ra}$ , based on components characterized by the Environmental Management Division, 88 ABW, Wright-Patterson. Many of these devices remain in static aircraft displays, but could be part of a past disposal operation that is under environmental restoration. For parts disposed in soils, it is reasonable to assume that containment provided by the device housing may be breached, and some of the material may exist in adjacent soils.

(b) DU. Table 13-11 contains some measurements on a DU aircraft counterweight. These measurements illustrate the relative contribution of photons and  $\beta$ -particles to the response of an unsealed ion chamber and pancake G-M probe. For both probes, the response from the bare

TABLE 13-9. AF RAM with Most Potential for Existence in Environmental Restoration Sites.

RAM	Source	Potential Locations
$^{226}\text{Ra}$	Self-Illuminating Dial Painting Operations	Interior: Floors, Sinks Exterior: Sewer Pipes, Soil
	Self-Illuminating Dials	Static Aircraft Displays (Intact & Leaking)
		Historical Aircraft Wreckage Burial and Burn Sites
DU	30 mm Ammunition	Firing Ranges and Testing Facilities
	Nuclear Weapons	Nuclear Weapon Accident and Burial Sites
		Nuclear Weapon Maintenance Materials Burial Sites
$^{\text{Nat}}\text{Th}$	MagTh Alloy	Historical Aircraft Wreckage Burial and Burn Sites
		Historical Missile Test Ranges
	Thoriated Lens Coatings	Historical Aircraft and Weapon Wreckage Burial and Burn Sites
WGP & HEU	Nuclear Weapons	Historical Nuclear Weapons Maintenance Burial Sites
$^3\text{H}$ , $^{85}\text{Kr}$ , $^{137}\text{Cs}$ , $^{85}\text{Kr}$ , $^{147}\text{Pm}$ , $^{60}\text{Co}$ , $^{241}\text{Am}$ , others	Electron Tubes, Spark Gap Irradiators, Gas & Aerosol Detectors	Historical Low-Level Radioactive Material Disposal Sites

TABLE 13-10. Common Characteristics of AF Self-Illuminating Devices with  $^{226}\text{Ra}$  (Mays 2005).

Category	Note	Quantity
$^{226}\text{Ra}$ Activity		1 – 3 $\mu\text{Ci}$ Typical 15 $\mu\text{Ci}$ Maximum
Ion Chamber Exposure Rate ( $\beta$ -Shield Open)	Device without Glass (i.e., no $\beta$ -shielding)	~ 5 mR/hr @ ~ 2 inches (Typical Gauge)
Ion Chamber Exposure Rate ( $\beta$ -Shield Closed)	Device with Glass (i.e., provides $\beta$ -shielding)	~ 2 mR/hr @ ~ 2 inches (Typical Gauge)



metal was dominated by  $\beta$ -particle response. Even for measurements with the protective aluminum cover, some instrument response could be attributed to  $\beta$ -particle interactions. This is due to the high energy  $\beta$ -particle emissions from  $^{234m}\text{Pa}$ . For this reason, pancake G-M are effective instruments for locating DU contamination, even if dispersed in soils.

TABLE 13-11. Example Measurements of a DU Aircraft Counterweight.

Instrument	Notes	Measurement	Probe Configuration
Victoreen 450B  (Note: response from $\beta$ -radiation has no practical meaning in units of exposure)	Bare Metal	66 mR/hr	On Contact, $\beta$ -Window Open
		6.6 mR/hr	On Contact, $\beta$ -Window Closed
	0.8 – 1 mm Aluminum (Al) Cover	3.6 mR/hr	On Contact, $\beta$ -Window Open
		1.6 mR/hr	15 cm from Surface, $\beta$ -Window Open
		2.5 mR/hr	On Contact, $\beta$ -Window Closed
		2.0 mR/hr	On Contact, $\beta$ -Window Closed, Probe Front
		0.7 mR/hr	15 cm from Surface, $\beta$ -Window Closed
ADM-300 BP-100	Bare Metal	560 kcpm	On Contact
	Bare Metal & 1 mm Plastic	270 kcpm	On Contact
	Al Cover	16 kcpm	On Contact
		8.6 kcpm	On Contact, Probe Back

## 14. Non-Destructive Inspection (NDI) and Other Industrial X-Ray Operations

a. General. The use of machine-generated x-rays for inspection of aircraft and its components is common in the AF. The use of x-ray systems by explosive ordnance disposal (EOD) and Office of Special Investigation (OSI) personnel are infrequent. Among these operations, there is an important distinction that has an impact on safety procedures: whether the facility is a shielded operation, where exposures are enclosed in a controlled area, or an unshielded operation, where exposures may be conducted in hangars, flightlines in deployed locations, or in other locations for EOD and OSI operations. In general, shielded operations will have fewer administrative requirements than unshielded ones because the engineering controls in shielded facilities make them inherently safer. Only a few of the NDI facilities in the AF are completely enclosed with shielding. This is logical since these facilities are expensive to build and often unnecessary due to the limited workloads of many NDI sections and low occupancy of areas adjacent to those areas. Many of the safety concepts provided here are similar to those considered for medical x-ray, except that industrial operations can have a greater degree of control because patients are not involved and are easier to control from a technical standpoint since the complexity of ALARA for patient exposure are not involved. As well, the medical environment has a greater level of concern for public exposure assessment because of the proximity of patients and visitors, while access to industrial x-ray areas is significantly more limited to members of the public.

b. BES Role. AF Technical Order (T.O.) 33B-1-1, Section 6.8, "Radiographic Inspection Safety," has the most extensive safety specifications among AF radiation operations. BES personnel that are responsible for NDI operations should be familiar with the T.O. NDI units have primary responsibility for radiation safety, with BES focusing on the following tasks:

- (1) delineation of restricted areas,
- (2) shielding and/or facility design for existing facility changes or new facility construction,
- (3) review of OIs for adequacy of radiation safety,
- (4) baseline radiation measurement surveys and re-survey when changes occur to the operation that impact the recommended controls of the baseline survey,
- (5) review personal radiation dosimetry results for compliance with investigation action levels (IAL), ALARA, and dose limits,
- (6) conduct radiation safety training,
- (7) conduct investigations of anomalous dosimetry and suspected overexposures, and
- (8) review the operation on at least an annual basis.

Because NDI shops should be reviewed on at least an annual basis, BES may designate it as a CAT 1 shop or a shop with special survey requirements.

c. Survey Measurements.

(1) Purpose. The primary purpose of survey measurements is to delineate restricted areas and determine appropriate control measures to ensure that ALARA and dose limits (Table 5-1) are met. For the small number of shielded facilities, measurements will be conducted to verify the effectiveness of shielding systems. In some cases, measurements may be necessary to investigate abnormal exposures or suspected overexposures. Like other workplace surveys, it is important to remember that while annual NDI shop visits are required for BES, survey measurements may not be required for annual visits unless significant changes in the operation occur that require updating from a baseline or previous survey.

(2) Survey Instruments. In general, x-ray exposure durations in NDI, OSI, and EOD operations have long durations as compared to those used for medical x-rays and have higher energy spectra. Because exposure durations typically encompass a large fraction of a minute to many minutes, most routine measurements can be collected with ion chambers and energy compensated G-Ms, like the ADM-300 internal probe, operating in "rate mode." Table 6-19 lists a number of instruments that are optimal and acceptable for use that meet the requirements of T.O. 33B-1-1. The table also lists many instruments that should **not** be used: Ludlum Model 19, pancake G-M probes, and the ADM-300 XP-100 "X-Ray Probe." For dose reconstructions or other measurements that require access to high radiation areas, it is recommended to use a subset of instruments listed in Table 6-19 that have the ability to operate in "integrate mode." Among ion chambers, the Victoreen 451P/B (or equivalent) is recommended (Table 6-8).

(3) Integrated Exposure in "Any One Hour" vs. Exposure Rate. It is important that in evaluation of exposures to recognize that restricted areas are designated by integrated exposure over any one (1) hour as compared to exposure rate that is often in the units of mR/hr. This is important to an operation like NDI and x-ray exposures in EOD and OSI because a significant fraction of time is spent setting up exposures, with perhaps no more than 25 % dedicated to active x-rays. For unshielded operations with limited space, advantage should be taken in developing restricted areas based on this factor. For example, the two (2) mrem in any one (1) hour, would be restricted by 10 mrem/hr if the on-time fraction was 20 %. For other operations where space is not limited, it may be easier to set restricted areas at two (2) mrem/hr.

(4) Occupancy Factors. Like medical x-ray radiation evaluations, the anticipated occupancy of various areas are used in shielded design plans and can be used in evaluating potential exposures to the general public and workers. Occupancy factors from T.O. 33B-1-1 are listed in Table 14-1, and are similar to those recommended for medical x-ray environments (Table 12-3). It is important to note that if these or facility-specific factors are used to delineate restricted areas, they are appropriate for use on long-term exposure limits, like the 100 mrem in a year for general public exposures. But they are inappropriate for use on limits based on one hour, like the two (2) mrem in any one hour restricted area limit and those used to delineate radiation area, and high and very-high radiation areas. The latter areas have specific "Caution" sign posting requirements specified in AFI 48-148 and described in Section 5.f.(3). Occupancy factors have greater use in shielded facilities due to co-location of offices, restrooms, etc., while unshielded operations are commonly accomplished in a hanger or on flightline tarmacs without these areas.

TABLE 14-1. Occupancy Factors for Shielding Planning Purposes (T.O. 33B-1-1, 1 Jan 05).

Occupancy	Area
Full (100 %)	X-ray control space and waiting space, darkrooms, film reading areas, workrooms, shops, offices, and corridors large enough to hold desks, living quarters, children's play areas, occupied space in adjoining buildings
Partial (25 %)	Worker restrooms, occupational use corridors too narrow for desks
Partial (12.5 %)	Public corridors too narrow for desks, utility rooms, employee lounges
Occasional (5 %)	Restrooms or bathrooms, storage rooms, vending areas, outdoor seating
Rare (2.5 %)	Outside areas used only for pedestrian/vehicular traffic, unattended parking lots, attic or crawl spaces, stairways, unattended elevators, janitors closets

## (5) Example Survey Measurements for an Unshielded NDI Shop.

(a) General. Figure 14-1 provides the layout of an example unshielded NDI x-ray operation conducted in a hanger building. In the figure, the aircraft is depicted with the nose

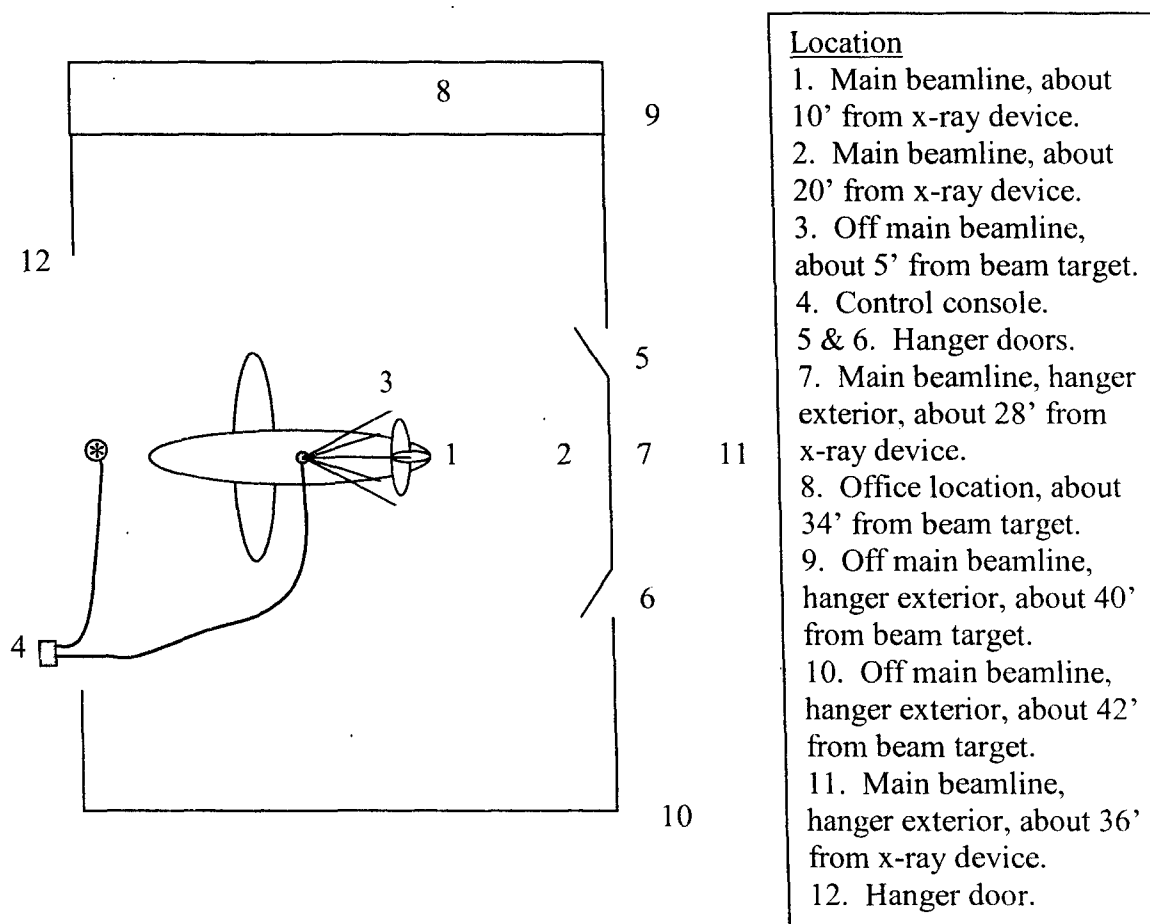


Figure 14-1. Example Unshielded NDI X-Ray Operation Set-up in Hanger.

pointed to the hanger opening on the left, with the x-ray device located inside the fuselage and the beamline directed upward toward the aircraft tail, forming an angle of 30 degrees between the main beamline and ground level. The operator is located at the console (#4), has visibility of a vast majority of the operation, and is located nearly opposite of the beamline, keeping radiation exposures low. T.O. 33B-1-1 recommends that the operator's console be located usually at least 75 feet from the x-ray device. The warning light is located in front of the nose of the aircraft and provides good visibility to individual's in the general area when the x-ray device is on. The hanger has two personnel entry doors on the rear of the hanger and offices at location #8. The rear and sides of the hanger are open concrete areas on the flightline tarmac. These locations have some vehicle traffic and may support temporary maintenance operations.

(b) Measurement Locations. A number of measurement locations were selected, based on the configuration of the operation. First, measurements should be collected at locations likely to be occupied by personnel during exposures, like the console (#4), observer location (#12), and offices (#8). Second, access points to the hanger, like the doors at locations 5 and 6 are important to measure. Third, while locations within the hanger should not be occupied during exposures, it is a good practice to assess potential exposure rates in close proximity to the x-ray machine for the purpose of evaluating the maximum hazard potential of the environment. Locations 1 and 2 are in closed proximity to the main beamline as it has passes through the tail of the aircraft which provides some scattering of the beam. Location 3 is in close proximity to the main beamline, but exposures should be only from target scattering and x-ray device leakage. Lastly, numerous locations on the rear of the hanger are measured because they have the potential to have uncontrolled access during exposures.

(c) Measurements. Table 14-2 contains measurements from the example NDI operation, under the assumption that they were collected with a Victoreen 451P pressurized ion chamber. At

TABLE 14-2. Exposure Measurements for Example NDI Operation Illustrated in Figure 14-1.

Location	Measurements		
	Integrated Exposure (mR)	Beam On-Time (minutes)	Exposure Rate (mR/hr)
1	27.3	2	820
2	12.0	4	180
3	9.0	4	135
4	Not Applicable	Not Applicable	0.08
5			14
6			13
7			24
8	4.9	27	0.18
9	Not Applicable	Not Applicable	0.4
10			0.3
11			12
12			0.08

locations 1, 2, 3, and 8, measurements were collected in the integrate mode, while other measurements were collected in rate mode. It is important that BES personnel understand that high exposure rate environments like those of locations 1, 2, and 3 should be measured remotely using integrate or "Freeze" modes. In some cases, high exposure rates can be measured in rate mode with an instrument's probe separated from the meter with an extension cable and pole. Using remote measurement methods like these are consistent with the ALARA principle. In this example, BES personnel observed multiple x-ray exposure shots and determined that the beam was on for only about 10 minutes during an hour, for a beam on-time fraction of 17 %. The hourly exposure rates are listed in Table 14-3 using 20 % as a conservatively-estimated maximum on-time fraction.

TABLE 14-3. Estimated Hourly Exposure Rates for Locations in Figure 14-1 based on Measurements from Table 14-2 and a Maximum On-Time Fraction of 20 %.

Location	Estimated Maximum Exposure in One Hour (mR)	Location	Estimated Maximum Exposure in One Hour (mR)
1	164	7	4.8
2	36	8	0.036
3	27	9	0.08
4	0.016	10	0.06
5	2.8	11	2.4
6	2.6	12	0.016

#### (d) Measurement Interpretation and Application.

1 General. In review of the data from Table 14-3, it is apparent that locations with forward-scattered radiation (i.e., the beam scattered in the same general direction of the primary beam) have the highest radiation exposure rates, evidenced by the measurements collected at locations 1, 2, 7, and 11. Locations that have more side or backscatter have significantly lower exposure rates than those subject to forward scattering. As well, the greater the separation distance from the source or source of scattering, the lower the exposure rate. In general, scattered radiation exposure levels should follow the  $1/r^2$  principle. In comparison of a few locations that are subject to a similar scattering environment, the exposure levels generally follow this rule. For example, location 2 has an exposure rate about one-fourth of that at location 1, with location 2 being twice as far from the source as location 1. The same relationship exists between exposure rates at locations 7 and 11, however, these exposure rates are proportionately much lower than those at locations 1 and 2 because of attenuation afforded by the hanger wall.

2 Delineation of Restricted Areas for One Hour Exposure Durations. Among locations measured at rear exterior locations, the highest estimated exposure rate was 4.8 mR in one hour, with measured locations at 30 cm from the hanger exterior wall having exposure rates ranging from 0.016 to 2.4 mR in one hour. During NDI operations, access to this exterior location must be restricted from the general public and non-radiation workers, since the estimated exposure in an hour was greater than 2 mrem. However, because estimated exposures do not exceed 5 mrem in any one hour, "Caution – Radiation Area" signs are not required for this area. Estimated exposures for

hanger interior locations have significant variability ranging from 27 to 164 mR in one hour, but will be significantly higher inside the aircraft in close proximity to the x-ray device from x-rays scattered from metallic surfaces of the aircraft and device leakage radiation. Clearly, since some areas in the hanger interior have estimated exposures greater than 100 mrem in one hour, this area should be posted with "Danger – High Radiation Area" signs. While locations in the main beamline from some x-ray devices could exceed 500 rad in an hour (very high radiation area) if exposed during a series of x-rays that normally would be collected over an hour. However, it is highly improbable that an individual could remain in these locations over the course of multiple measurements, where NDI technicians are retrieving and replacing x-ray films, and re-orienting the x-ray device. Therefore, the posting of "Grave Danger – Very High Radiation Area" signs are not justified for routine NDI operations. The methodology for posting the interior (or access points to) of the hanger can be varied. For example, at access locations, where radiation areas exist could be posted with "Caution – Radiation Area" signs, with "Danger – High Radiation Area" signs being posted in closer proximity to the aircraft where estimated exposure rates exceed 100 mrem in one hour. In lieu of two-level of postings for the interior (or access points to) of the hanger it may be simpler to post only "Danger – High Radiation Area" signs.

**3 Delineation of Restricted Areas for Annual Estimated Exposures.** To evaluate compliance with the general public exposure standard of 100 mrem in a year, annual NDI workload for this facility needs to be estimated or based on actual NDI exposure log information. In general, many of the unshielded NDI operations are conducted in this manner because of the small volume of work, lacking justification for the expense of a shielded facility. Some facilities may conduct x-ray operations for periods of 100 hours or less. For this example, if the annual operation in this hanger was for 100 hours, estimated annual exposures for some measured locations from Figure 14-1 are in Table 14-4. The locations listed are only those locations that have reasonable probability for occupancy by members of the general public or non-radiation workers. From the table, only location 7 had an estimated annual exposure in excess of the 100 mrem limit. This location among others on the rear exterior of the hanger had restricted access because estimated exposures exceeded the limit of 2 mrem in any one hour. Other locations, like the office and the front of the hanger that are

TABLE 14-4. Estimated Annual Exposures for Locations in Figure 14-1 based on Hourly Exposure Rate from Table 14-3 and 100 hours of Use per Year.

Location	Occupancy Factor* (Table 14-1)	Estimated Maximum Exposure in One Hour (mR)	Estimated Annual Exposure (mR)
4	2.5 %	0.016	0.04
5	25 %	2.8	70
6	25 %	2.6	65
7	25 %	4.8	120
8	100 %	0.036	3.6
9	25 %	0.08	2.0
10	25 %	0.06	1.5
11	25 %	2.4	60
12	2.5 %	0.016	0.04

\* Members of general public and/or non-radiation workers.

expected to have rare occupancy by members of the general public or non-radiation workers, do not require restricted access.

(e) Other Considerations.

1 Multiple Configurations. The example provided here had a simplified exposure scenario with the beam directed in only one direction. For most NDI operations of this type, multiple exposure configurations will be used. As such, delineation of restricted areas in and surrounding a hanger will require analysis of all scenarios to ensure adequate protection for members of the public and non-radiation workers.

2 Sky Shine. This example had office space on ground level. Many hangers that have been modified over the years have occupied office space on multiple levels. An important consideration for NDI exposures, when the x-ray beam is directed upward, is the potential for scattered radiation off hanger structural members and the roof, and direct transmissions. Scattered radiations could create high exposure levels in upper levels of the hanger (or other structure) that need to be addressed. As well, roof access will have to be restricted during exposures. This may require locked fences and the posting of temporary radiation caution or danger signs.

3 Documentation. Survey results, and the interpretation and application to exposure standards are important to document in shop folders. Like the example provided for a RAM storage area, Figure B-2, it is important to provide an adequate description of the operation to include a diagram, names of individuals conducting the survey, survey instruments used, survey instrument calibration certificates, survey results, application of survey results to exposure standards, ALARA considerations, and required administrative and engineering controls.

4 Thermoluminescent Dosimeters (TLDs). TLDs measurements can be used as a supplement to portable survey instruments measurements in evaluating exposures. While they can be used for short-term measurements, they are most commonly used for evaluating long-term exposures, like a calendar quarter, where the results can be normalized to estimate adherence to annual general public exposure limits. For the example provided here, it would be effective to place TLDs in office areas where occupancy by non-radiation workers is expected to be high. Whenever TLD studies are accomplished, it is important to document the results in a report, similar to that accomplished for portable instrument surveys.

5 Administrative Procedures. BES personnel are adept at making workplace exposure assessments evaluations and often heavily concentrate their efforts in these areas. Regardless of the quality of your assessment and control recommendations, the effectiveness of a radiation safety in unshielded operations resides with NDI personnel. Most abnormal- or over-exposures in NDI are not the result of deficient safety recommendations, rather they are due to lack of implementation. Therefore, during shop visits observe NDI personnel during routine operations as much as practical and evaluate adherence to operating instructions and good safety practice.



d. Example Over-Exposure Investigation.

(1) General. Among radiation work areas in the AF, unshielded NDI operations have the greatest potential for abnormal- and over-exposures among AF workers. The primary cause of these incidents is omission of required administrative controls by NDI technicians. The example provided here will use the basic configuration of Figure 14-1, but the x-ray device was on the exterior of the aircraft directed through the tail to the nose portion of the aircraft, as shown in Figure 14-2. The example provided here closely tailors an actual AF NDI incident.

(2) Circumstances of Overexposure Investigation. NDI personnel were performing a shot of an aircraft tail as shown in Figure 14-2, with a 60 second exposure. After equipment and film were positioned, NDI personnel cleared the area and initiated the shot. NDI personnel then left the console and safety monitor positions to complete paperwork in a nearby vehicle. During the exposure, a technician from another shop entered the rear hanger door and accessed the aircraft to search for a misplaced T.O. The technicians had a path as illustrated by the dotted line in the figure. After the technician left the aircraft, the safety monitor had returned to their monitoring position and notified the NDI supervisor. The NDI supervisor immediately called BES.

(3) BES Investigation. T.O. 33B-1-1 lists procedures that must occur after a suspected overexposure. NDI personnel should already have documented vital information surrounding the incident to include involved individuals, exact positions and duration of exposure, collection of all dosimeters, reading of all pocket ion chambers or EPDs as applicable, and acquiring signed statements from individuals involved. For individual's that had dosimetry monitoring during the incident, BES should determine whether additional measurements are necessary, based on circumstances surrounding the incident, EPD or pocket dosimetry results, and past survey measurements conducted in the shop. If involved individuals were not wearing dosimetry, BES will have to conduct dose-reconstruction measurements.

(4) BES Dose Reconstruction. Portable survey instruments and/or TLDs can be used to conduct dose reconstructions. For use of portable instruments, remote measurement techniques shall be used, as exposures to BES personnel in high radiation areas are unnecessary and violate the ALARA principle. As noted above, integrate or "Freeze" modes can be used for portable measurements. For the example illustrated in Figure 14-2, based on the exposed technician's statement, it was estimated that about six seconds elapsed in walking from the hanger door to the aircraft entry point, 30 seconds were spent in aircraft (along the illustrated path), and another six seconds were spent exiting the hanger. The technician's path is broken into somewhat equal lengths and numbered. Locations 1 through 6 are assumed to be the same as 16 – 21 (17 – 21 not being displayed on the Figure). To estimate the total exposure, a remote integrated measurement was collected at locations 1 through 16, with exposure times being 15 and 30 seconds, respectively for measurements in the aircraft and outside. As shown in Table 14-5, each location has an estimated occupancy time, under the assumption that the exposure at the discrete measurement locations summed approximates the actual exposure. For example, since it was estimated that the technician spent 30 seconds in the aircraft and the path in the aircraft was broken into nine measurement locations, the time spent per location is listed as 3.33 seconds. The measurements are listed in Table 14-5 with calculation of the exposure for each location. The total estimated exposure for this investigation is 429 mR (~ 429 mrem). Since this individual was a non-radiation worker, this

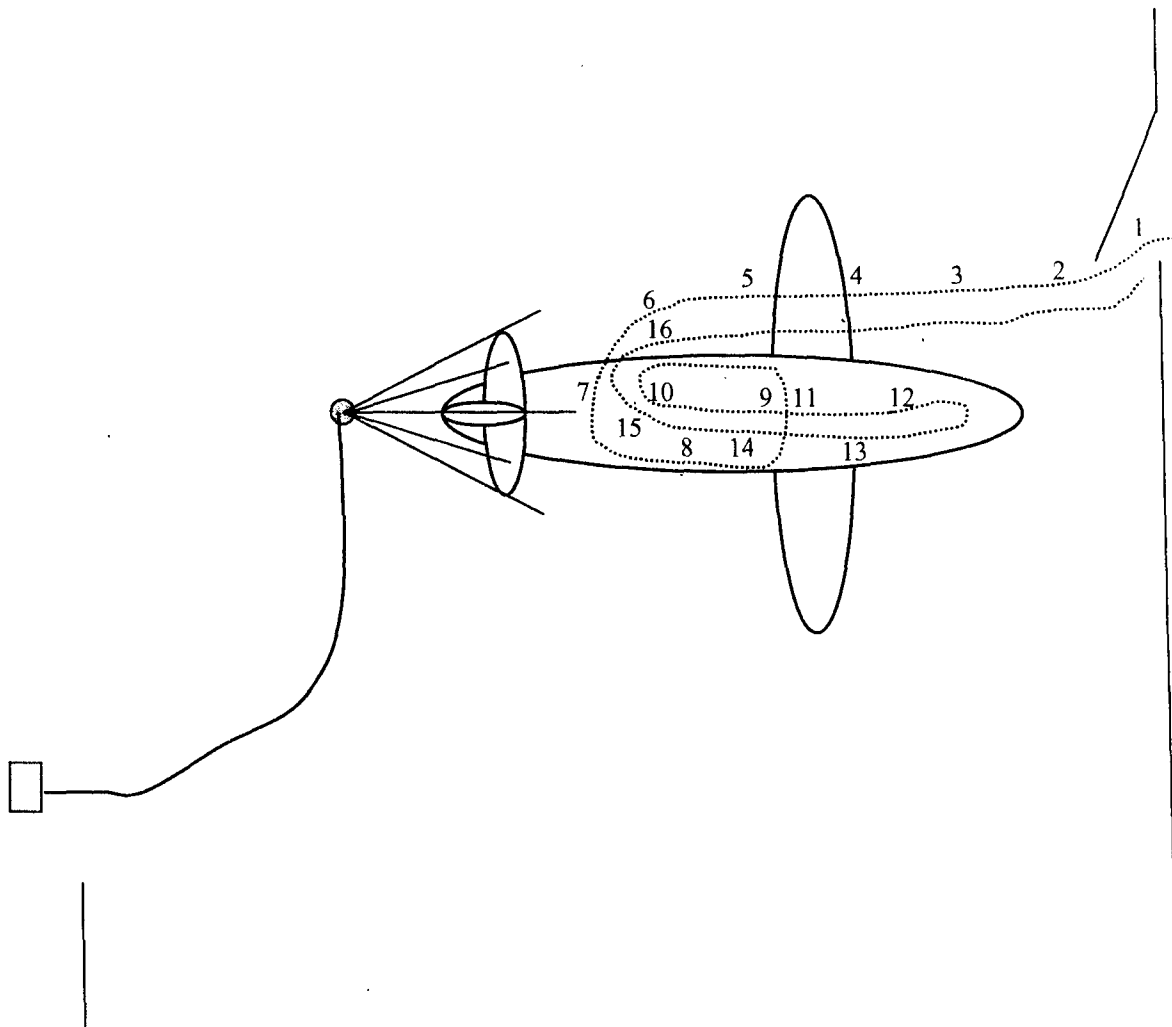


Figure 14-2. Example of Overexposure Investigation.

exposure was categorized as an overexposure, as the annual limit for non-radiation worker and the general public is 100 mrem.

(5) Other Aspects of the Investigation. In the actual investigation that this example is tailored after, many safety procedures specified in T.O. 33B-1-1 were violated. First, the rear hanger door was not secured, nor posted with a radiation caution or danger sign. Second, no barrier cones, ropes, or visible warning beacons were used. Third, radiation caution or warning signs were not posted at any location in the hanger. Lastly, the safety monitor and control console were not manned. All of these administrative controls are vital to safe, unshielded operations, but omitted!

e. Annual NDI Shop Visits. Annual shop visits are required for NDI operations because annual exposure assessments must be made on radiation workers, non-radiation workers, and general public

per AFI 48-148. Re-accomplishment of survey measurements are not necessary if previous measurements adequately characterize the radiation hazards. Table B-5 contains a checklist of key radiation safety items that BES should review annually.

f. OSI and EOD Operations. OSI and EOD x-rays operations are performed on an infrequent basis as compared to those of NDI. Because of the infrequent OSI and EOD operations, affected areas can normally be cleared of unnecessary personnel and members of the general public to alleviate these exposure issues. BES should review operating instructions for these operations to ensure that adequate safety zones are specified. In general, because of the infrequent operations, the exclusion zone will likely be based solely on the two (2) mrem in any one hour limit for members of the public and non-radiation workers.

TABLE 14-5. Dose-Reconstruction Measurements for Example Overexposure Investigation.

Location	Time Spent at Location (s)	Measurement Time (s)	Measured Exposure (mR)	Estimated Actual Exposure (mR)
1	1	30	54	1.8
2	1	30	69	2.3
3	1	30	90	3.0
4	1	30	126	4.2
5	1	30	198	6.6
6	1	30	330	11
7	3.33	15	392	87
8	3.33	15	95	21
9	3.33	15	126	28
10	3.33	15	108	24
11	3.33	15	104	23
12	3.33	15	72	16
13	3.33	15	419	93
14	3.33	15	68	15
15	3.33	15	288	64
16	1	30	330	11
17	1	30	198	6.6
18	1	30	126	4.2
19	1	30	90	3.0
20	1	30	69	2.3
21	1	30	54	1.8
			Total	429

## 15. Laboratory Analysis of Radioactive Material Samples

a. General. BES routinely send radiological samples to AFIOH's Radioanalytical Branch for analysis. NRC-regulated RAM possessed on an AF permit from the RIC, must be analyzed by AFIOH/SDRR, or other NRC or agreement state approved laboratories. This section provides BES with information on the selection of the proper analytical method, interpretation of analytical results, and application to limits.

b. Sample Analysis Methods. The most common sample type sent to AFIOH/SDRR for radioanalysis are leak tests. Swipes, air filters, and soil samples are other common types. Table 15-1 contains a listing of common sample types and the most common analytical methods accomplished by AFIOH/SDRR. The analytical method chosen is dependent on the purpose of the sample and type. For details on sampling procedures and a complete listing of AFIOH/SDRR capabilities, visit their web-site.

TABLE 15-1. AFIOH/SDRR Most Common Analytical Methods for Common Sample Types.

Sample Type	Method				
	Gross- $\alpha/\beta$	Gross- $\gamma$	$\alpha$ -Spectroscopy	$\gamma$ -Spectroscopy	Liquid Scintillation
Leak Test Analyses	$\alpha/\beta$ -, $\alpha$ -, or $\beta$ -emitters, (except low-energy $\beta$ -emitters)	Electron-capture isotopes ( $^{109}\text{Cd}$ , $^{57}\text{Co}$ )	Uncommon	Occasional, follow-on to elevated screening measurements	Low-energy $\beta$ -emitters ( $^3\text{H}$ , $^{63}\text{Ni}$ , $^{14}\text{C}$ )
Swipe Samples			Occasional		
Air Filter Samples		Uncommon	Yes, for specific elements like Th, U, Pu, Am	Yes, most common initial analysis method	Uncommon
Soil Samples	Sometimes, only serves screening purpose (inherent high variability)				Occasional (low-energy $\beta$ -emitters)

(1) Specific vs. Non-Specific Methods. Some of the analytical methods, like gross- $\alpha/\beta$  and gross- $\gamma$  are not radionuclide-specific and sometimes used for screening samples, whereas the other three methods listed provide radionuclide-specific information. For example, when leak tests or swipes are being accomplished on a known RAM source, a gross- $\alpha/\beta$  or - $\gamma$  method can be used under the assumption that the net activity detected on the sample can be attributed solely to that radionuclide. However, for unidentified RAM, screening methods like these cannot identify radionuclides, except that it does provide information on relative activities of  $\alpha$ -,  $\beta$ -, and  $\gamma$ -radiations, that can be used to refine the list of potential radionuclides.  $\gamma$ -spectroscopy is the most common method accomplished on soils, as most RAM contaminants in soils from AF operations are readily identified by  $\gamma$ -radiation emissions. For some of these analyses, further element-specific  $\alpha$ -spectroscopy analyses are accomplished to more accurately assess a contaminant identified in the

initial  $\gamma$ -spectroscopy analysis. Uranium  $\alpha$ -spectroscopy is most common in the AF because it allows better differentiation between DU and  $^{Nat}U$ , especially in soil and urine bioassay samples where  $^{Nat}U$  is always present.

(2) AFIOH Analysis vs. Private Sector Laboratories. AFIOH is centrally-funded to provide analytical services to permitted RAM used in the AF. Permittees have the option of using private sector laboratories that are NRC or agreement state approved at their own expense. Besides the cost savings, there are other advantages to using AFIOH/SDRR. First, AFIOH is familiar with AF operations and will make corrections in requested analyses if an obvious error is made by BES, while private laboratories may not do this. Second, primarily for soils, the laboratory will archive samples for a period of time that will allow more specific follow-on analyses, like  $\alpha$ -spectroscopy, if the  $\gamma$ -spectroscopy analyses do not provide sufficient information. Private laboratories normally dispose of samples shortly after analyses are complete necessitating the expense of re-sampling if additional analyses are required. Last, AFIOH archives analytical results indefinitely, allowing new reports if originals are misplaced.

(3) Bioassay Samples. Information on bioassay samples and analytical methods is purposely omitted from this document because it is recommended that AFIOH/SDRR be consulted on all routine and special bioassay samples. While private sector approved laboratories can be used for bioassay analyses, this practice is not advised because intakes of NRC-licensed RAM and resultant internal radiation dose must be documented in the AF Master Radiation Exposure Repository (MRER). MRER records have associated quality assurance/quality control information on-site for external and internal dose assessments if accomplished by AFIOH/SDR. However, private laboratories do not generally have the technical capability to compute RAM intake and internal radiation dose.

(4) Reporting Units. BES personnel often contact AFIOH/SDRR with questions regarding the units analytical results are reported. Most analytical results are reported in scientific notation (e.g.,  $2.0 \text{ E-6 } \mu\text{Ci}$ ), where the term "E-6" is not commonly used by individuals without science and engineering training. This term is a simplified notation for " $\times 10^{-6}$ ." Thus,  $2.0 \text{ E-6 } \mu\text{Ci} = 2.0 \times 10^{-6} \mu\text{Ci} = 2.0 \text{ pCi}$ .

#### c. Leak Test Analyses, Swipe Samples, and Air Filters.

(1) General. For sample analysis requests through AFIOH/SDRR, it is important that when filling out the AF Form 495 that the radionuclide(s) being tested for be listed on the form. This will allow the laboratory to ensure that the proper analysis is accomplished. If the source is unknown, state this on the form, this will ensure that the sample is subjected to gross- $\alpha/\beta$  and gross- $\gamma$  screens.

(2) Leak Test Analyses. Table 15-2 lists the common analytical methods for the most common sealed source leak tests conducted in the AF. When the results of analyses are acquired by BES, it is their responsibility to interpret the results for compliance with allowable levels of leakage specified by permit condition. Most sources have a limit of **0.005  $\mu\text{Ci}$**  of removable contamination. BES also has a responsibility to ensure that the proper test was conducted, and this is especially important if a private sector laboratory is used. For interpretation of analytical results, the reported activity for  $\alpha$ -emissions should be corrected for self-absorption by the sample medium. An example

of leak test pre-screening is provided in Section 9.c.(2). In the example, a swipe collection efficiency of 0.25 is also applied to the analysis. While this practice is rigorous and provides the best estimate of RAM leakage, in reality, leaks in sealed sources are uncommon and most sealed sources will have reported activities (from AFIOH/SDRR) less than  $2 \times 10^{-6}$   $\mu\text{Ci}$ . Therefore, application of  $\alpha$ -particle self-absorption and collection efficiency factors will not change the conclusion: any leakage is below the limit. Additionally, if a swipe sample has an activity greater than 9 pCi ( $9 \times 10^{-6}$   $\mu\text{Ci}$ ), it is standard practice for AFIOH/SDRR to contact the customer.

TABLE 15-2. Leak Test Analyses for Common AF Sealed Sources Requiring Periodic Leak Testing.

Radionuclide	Analytical Method	Radionuclide	Analytical Method
C-14	Liquid Scintillation	Sr-90/Y-90	Gross- $\alpha/\beta$
Fe-55	Gross- $\gamma$	Cd-109	Gross- $\gamma$
Co-57	Gross- $\gamma$	Cs-137	Gross- $\alpha/\beta$
Co-60	Gross- $\alpha/\beta$	Ra-226	Gross- $\alpha/\beta$
Ni-63	Liquid Scintillation	Am-241	Gross- $\alpha/\beta$

(3) Swipe Samples. Like leak test samples, the reported results from AFIOH/SDRR and other laboratories do not account for self-absorption by the sampling medium (normally filter paper). As well, this is a problem as well for low-energy  $\beta$ -particles. For analysis of swipe samples with suspected low-energy  $\beta$ -particles, liquid scintillation is preferred over gross- $\alpha/\beta$ . Again, proper annotation of the AF Form 495 with radionuclide information will ensure proper analyses are accomplished.

(4) Air Filters. AFIOH/SDRR analyzes most routine air sampling filters through the same methods as used for leak and swipe samples, except that it is standard practice to wet-ash (i.e. chemically destroy the filter) samples and plate residual materials on a metal planchet. In this geometry,  $\alpha$ -particle self-absorption correction to detection efficiency should not be performed by BES as it is taken into account in the laboratory analysis. In contrast, air filter analyses for gross  $\alpha$ -radiation using portable field instruments (see Section 9.c.(3)) by BES personnel must incorporate  $\alpha$ -particle self-absorption correction.

d. Drinking Water Samples. Table 15-3 contains National Primary Drinking Water Regulations maximum contaminant levels for radionuclides. Most samples handled by BES are sent to private sector laboratories. Interpretation of analytical results is generally made on the sample analysis report.

TABLE 15-3. National Primary Drinking Water Regulations, Maximum Contaminant Levels for Radionuclides (40 CFR 141.77, 1 Jul 04).

Category	Standard
Combined Ra-226 and Ra-228	5 pCi/L
Gross $\alpha$ -Particle Activity (excluding radon and uranium)	15 pCi/L
$\beta$ -Particle and Photon Radioactivity from Man-Made Radionuclides	4 mrem/yr ( $^{90}\text{Sr}/^{90}\text{Y}$ : 8 pCi/L) ( $^3\text{H}$ : 20,000 pCi/L)
Uranium	30 $\mu\text{g/L}$ (20 pCi/L for $^{\text{Nat}}\text{U}$ mix)

e. Soil Sample Analyses. Soil samples are generally collected by BES to investigate the potential for RAM contamination. As discussed in Section 13.c.5), BES may investigate potentially affected areas with field portable  $\gamma$ -spectroscopy systems like the SAM-935. It is recommended that follow-on laboratory analysis be performed to achieve superior accuracy and thorough identification. As shown in Table 15-1, most samples sent to AFIOH/SDRR are initially screened by high-resolution  $\gamma$ -spectroscopy. BES may interpret the analytical reports or request professional review by AFIOH/SDRR. In reviews by BES, it is important to understand that analytical reports will normally have a listing of all radionuclides detected, in addition to suspected contaminants. All soil contains naturally-occurring RAM, with the important ones listed in Table 13-8, and typical concentrations in U.S. surface soils summarized in Table 15-4. As noted in Section 13, many of these isotopes are observed in common AF RAM (i.e.,  $^{226}\text{Ra}$ , DU, and MagTh).

TABLE 15-4. Background Concentrations of Some Primordial Radionuclides in Surface Soil (Summarized from Myrick 1983).

Radionuclide	Number of Samples	Concentration (pCi/g)		
		Range	Mean	Standard Deviation
Ra-226	327	0.23 – 4.2	1.1	0.48
Th-232	331	0.10 – 3.4	0.98	0.46
U-238	355	0.12 – 3.8	1.0	0.83
K-40	NA	0.8 – 29	[In Rock (Eisenbud 1987)]	

## References

- ACC, "Bioenvironmental Engineering Environmental Field Manual," Field Manual 00-1, Vol. 1, HQ ACC, Langley AFB VA, Feb 2000.
- Bicron Measurements Products, "Model PGM Pancake GM Probe, User's Manual," 27 September 1996.
- Canberra Industries, "Type Test Energy – Modified Lo-Range Detector," September 2004.
- Cardinal Health, "Ion Chamber Survey Meter with Beta Slide Technical Specifications – Inovision Model 451B," 2003.
- Cardinal Health, "Pressurized  $\mu$ R Ion Chamber Survey Meter Technical Specifications – Inovision Model 451P," 2003.
- DG-4006, "Demonstrating Compliance with the Radiological Criteria for License Termination," Draft Regulatory Guide, U.S. Nuclear Regulatory Commission, Washington D.C., August 1998.
- DoD, "Nuclear Weapons Accident Response Procedures (NARP)," Under Secretary of Defense for Acquisition, Technology, and Logistics, DoD 3150.8M, February 2005.
- Eberline, "Operations Manual Model RO-2 Ion Chamber," Thermo Electron Corp., February 1983.
- Eisenbud, M., "Environmental Radioactivity," Third Edition, Academic Press, San Diego, 1987.
- IATA, "Dangerous Good Regulations," International Air Transport Association, 45<sup>th</sup> Ed, Montreal – Geneva, 2004.
- Ludlum Measurements Inc., "Model 42-5 Neutron Ball Cart Specification Sheet," 2005.
- Ludlum Measurements Inc., "Model 42-9 Proportional Detector Specification Sheet," 2005.
- Ludlum Measurements Inc., "Model 44-9 Pancake G-M Detector Specification Sheet," 2005.
- Ludlum Measurements Inc., "Model 44-38 Energy Compensated G-M Specification Sheet," 2005.
- Ludlum Measurements Inc., "Ludlum Model 19 Micro R Meter Operators Manual," 1997.
- Mays, Mark L., "Radiation Protection Program for the M43A1/M8A1 Chemical Agent Alarm, Chemical Agent Monitor, Improved Chemical Agent Monitor, GID-3 Automatic Chemical Agent Detector/Alarm, 88<sup>th</sup> ABW Environmental Management Division, W-P AFB OH, Revision 2, March 2004.



Mays, Mark L., Personal Communication, May 2005.

Montgomery, James D. "Radiological Hazard Assessment of the Ultra Image Digital Radiology System for Proposed Air Force Nondestructive Inspection (NDI) Operations, Armstrong Laboratory, Consultative Letter, AL/OE-CL-1997-0029, Brooks AFB TX, 31 Jan 1997.

Myrick, L., et al, "Determination of Concentrations of Selected Radionuclides in Surface Soils in the U.S.," Health Physics, Vol. 45, No. 3, 1983.

Nichelson, Scott M. "Correction Factor for ADM-300 AP-100 Alpha Probe," Air Force Institute for Operational Health, Consultative Letter, IOH-SD-BR-CL-2004-0058, Brooks AFB TX, 29 Jun 04.

OEHL, "A Broken Arrow Guide for Bioenvironmental Engineers," Occupational and Environmental Health Laboratory Report 83-115RZ111CXX, Brooks AFB TX, 4 April 1983.

NCRP, "Structural Shielding Design and for Medical X-Rays and Gamma Imaging Facilities," National Council on Radiation Protection and Measurements, Report No. 147, 2004.

NRC Industries, "RemRad Radiation Monitoring Systems, Operators Manual – ADM-300 Multi-Function Survey Meter," 1991.

NRC, "Minimum Detectable Concentrations with Typical Survey Instruments for Various Contaminants and Field Conditions," NUREG/CR-1507, U.S. Nuclear Regulatory Commission, Washington D.C., December 1997.

NRC, "Decision Methods for Dose Assessment to Comply with Radiological Criteria for License Termination," NUREG-1549, U.S. Nuclear Regulatory Commission, March 1998.

NRC, "Consolidated Guidance about Materials Licenses – Program-Specific Guidance about Licenses of Broad Scope," NUREG-1556, Volume 11, U.S. Nuclear Regulatory Commission, Washington D.C., April 1999.

NRC, "Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)," NUREG-1575, U.S. Nuclear Regulatory Commission, Department of Energy, Environmental Protection Agency, Department of Defense, Washington D.C., December 1997.

NRC, "Radiological Surveys for Controlling Release of Solid Materials," NUREG-1761, U.S. Nuclear Regulatory Commission, Washington D.C., July 2002.

NRC, "Residual Radioactive Contamination from Decommissioning," NUREG-5512, Volume 1, U.S. Nuclear Regulatory Commission, Washington D.C., 1992.

NRC, "NRC Regulatory Issue Summary 2005-03, 10 CFR Part 40 Exemptions for Uranium Contained in Aircraft Counterweights – Storage and Repair," RIS 2005-03, 28 Feb 05.

Rademacher, S.E., "Data from the Remediation of RW-37, Travis AFB CA," 2002.

Rademacher, S.E., "The Influence of Heterogeneity in Gamma Spectroscopy Analysis of Soil Contaminated with Weapons Grade Plutonium at the BOMARC Missile Accident Site, McGuire AFB NJ," Report IERA-SD-BR-SR-2001-0006, Air Force Institute for Environment, Safety and Occupational Health Risk Analysis, Brooks AFB TX, Oct 2001.

RRSSD, "Registry of Radioactive Sealed Sources and Devices, Safety Evaluation of Device, Model No. 3400 Series Troxler Gauges," No. NC-646-D-130-S, 28 December 2003.

Scleien, B., "The Health Physics and Radiological Handbook," Scinta Inc, 1992.

Scott, James R *et al*, "Broken Arrow Checklist for Bioenvironmental Engineers," Occupational and Environmental Health Laboratory Report 84-001RZ111KXX, Brooks AFB TX, October 1983.

Sheely, Eugene V., "Personal Communication – Measurement of Sampling Area of ADM-300, AP-100 Probe," Defense Nuclear Weapons School, Defense Threat Reduction Agency, Kirtland AFB NM, 12 Apr 05.

Storm, E.; Lier, D.W.; Watanabe, T.; Health Physics, Volume 26, 1974.

Victoreen, "Operation and Instruction Manual – Ion Chamber Survey Meter, Model 450P," Victoreen Inc, July 1993.

Victoreen, "Instruction Manual – Survey Meter, Model 471RF," Victoreen Inc, October 1980.

Victoreen, "Operating Instructions – Model 470A, Panoramic Survey Meter," Victoreen Inc, 1976.

Whatman, "Whatman 934-AH Glass Microfiber Product Specification," Whatman International, Ltd, 2005.

Wrobel, M., "Dosimetry in Diagnostic Radiology; A Guide for Meeting JCAHO and ACR Requirements and ICRP Recommendations," Armstrong Laboratory, Occupational and Environmental Health Directorate, Brooks AFB TX, AL/OE-TR-1997-0162, Jan 1997.

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## **Appendix A**

### **Instrument Energy Response Plots**

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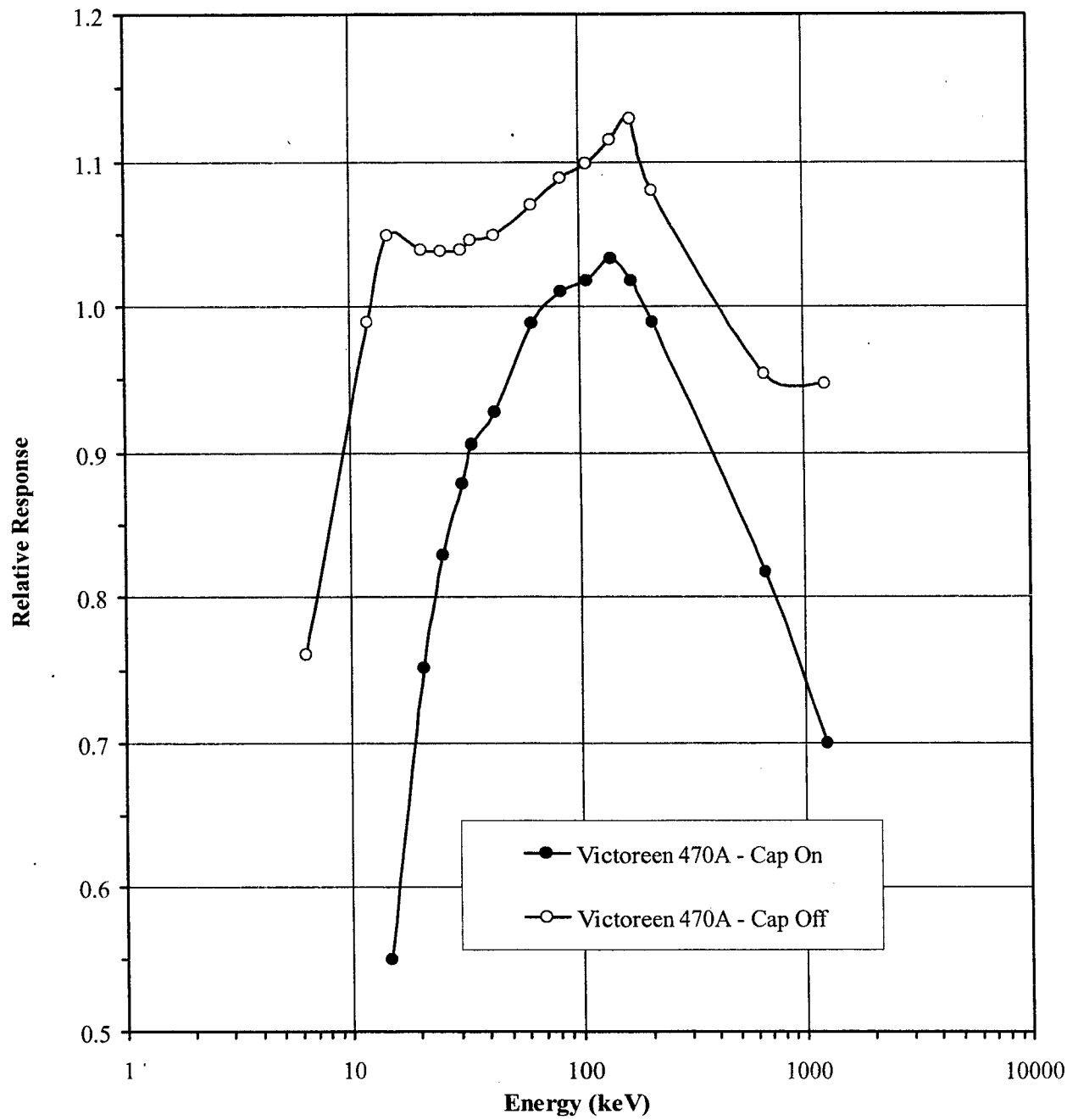


Figure A-1. Relative Energy Response of the Victoreen 470A Ion Chamber (Victoreen 1976).

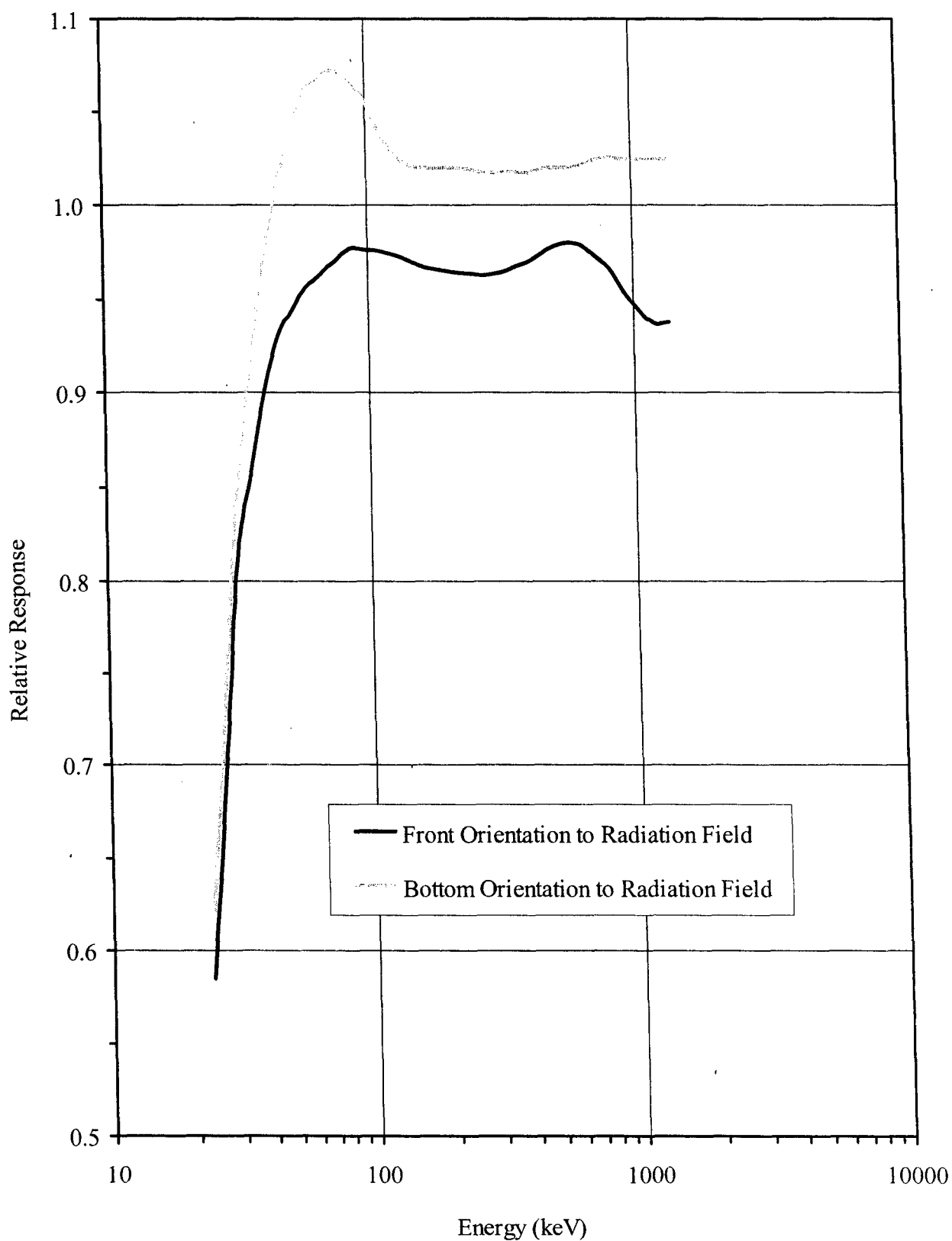


Figure A-2. Relative Energy Response of the Victoreen 450P Ion Chamber (Victoreen 1993).



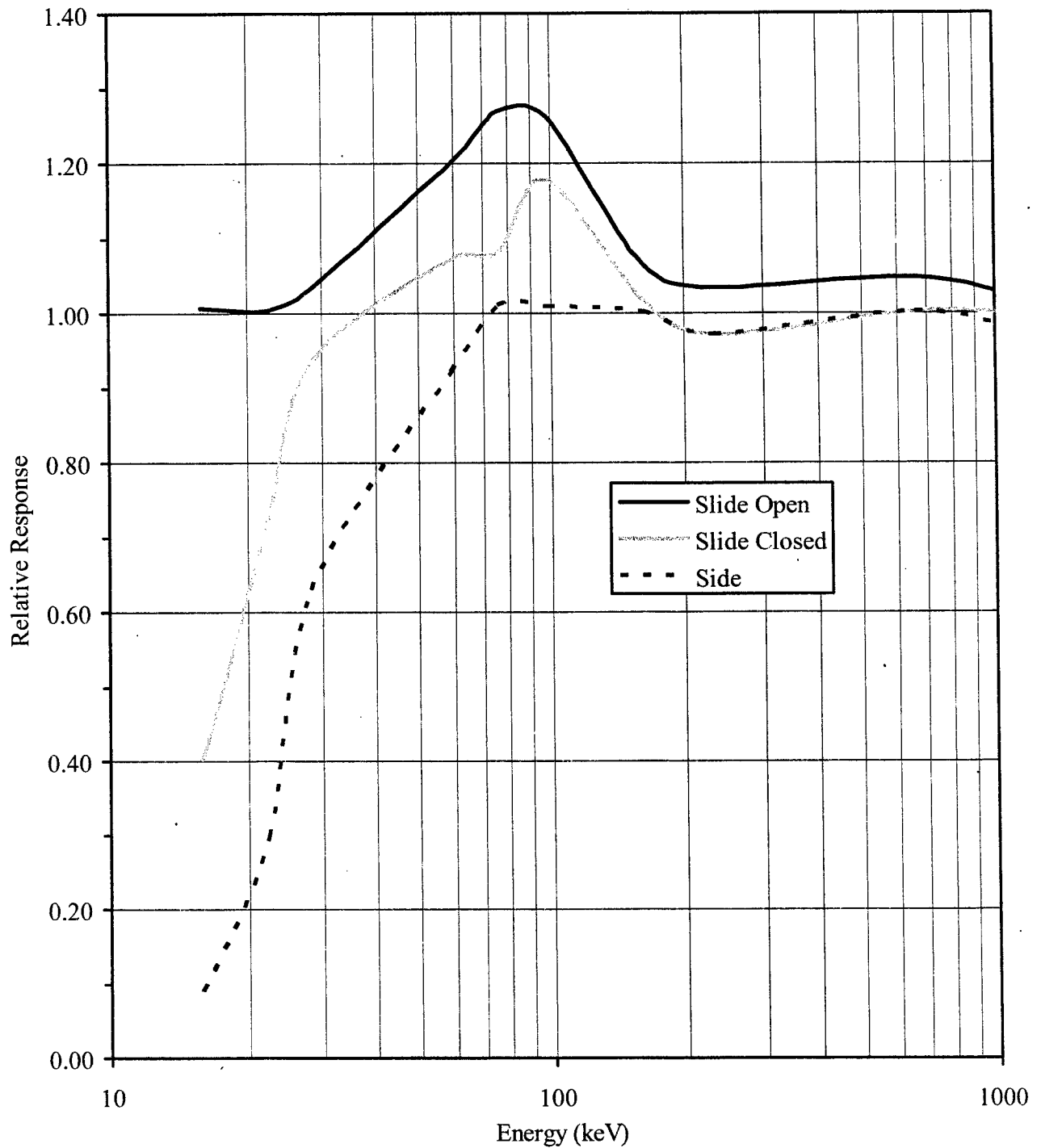


Figure A-3. Relative Energy Response of Eberline RO-20 Ion Chamber (Thermo Electron 2005).

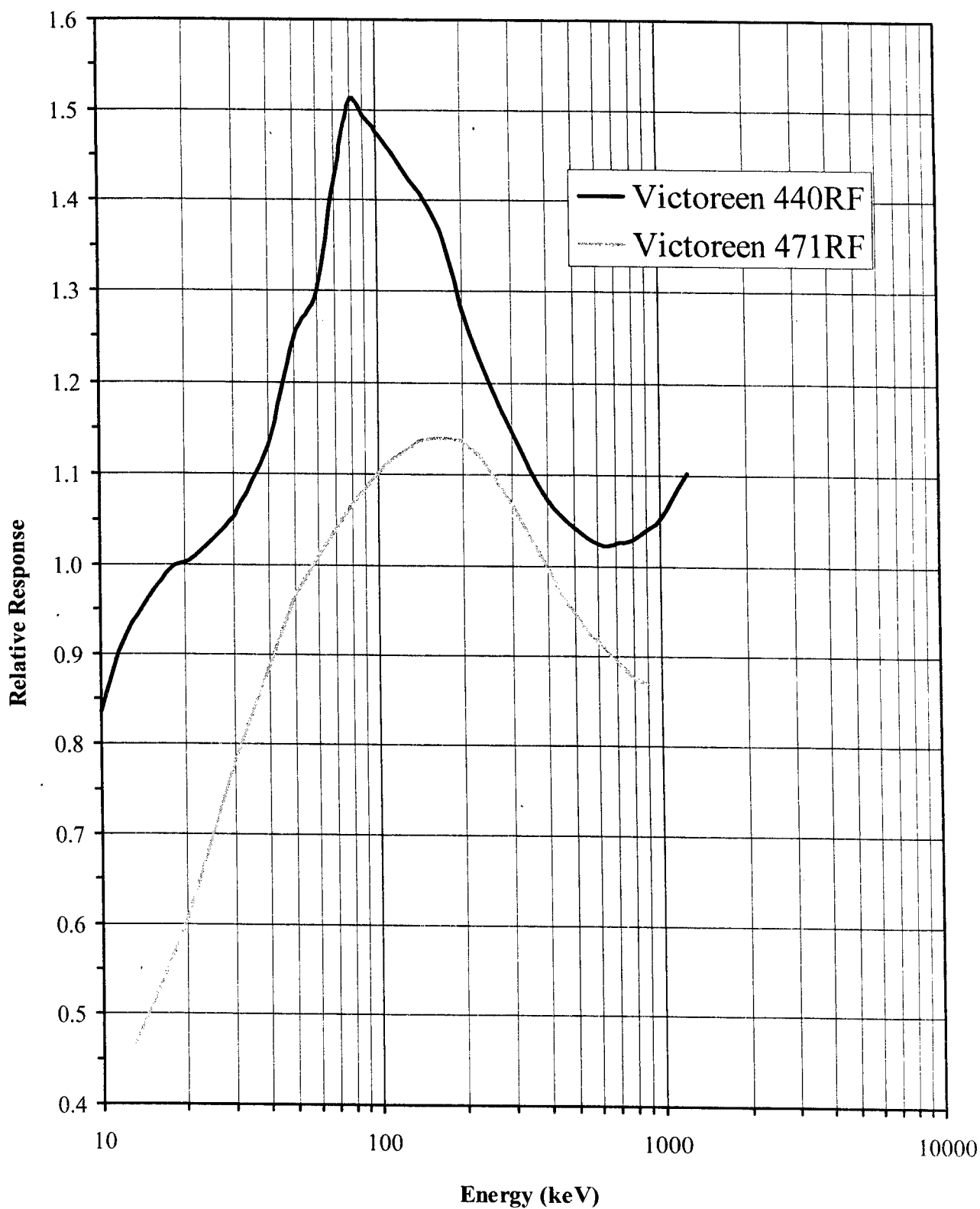


Figure A-4. Relative Energy Response of the Victoreen 440RF/D Ion Chamber (Victoreen 1990) and 471RF Ion Chamber (Victoreen 1980).

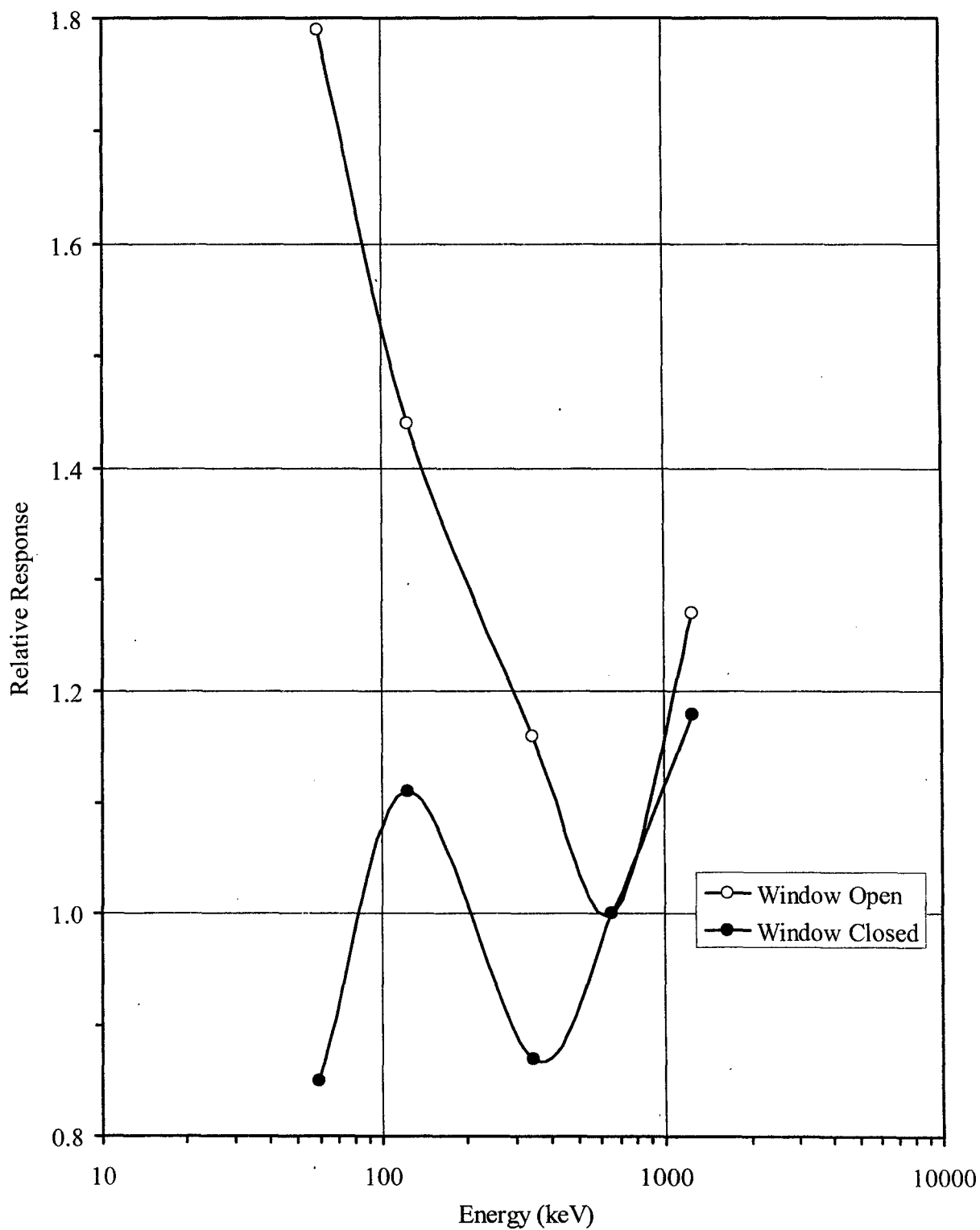


Figure A-5. Relative Energy Response of the Ludlum Model 44-38  
Energy Compensated G-M Probe (Ludlum 2005).

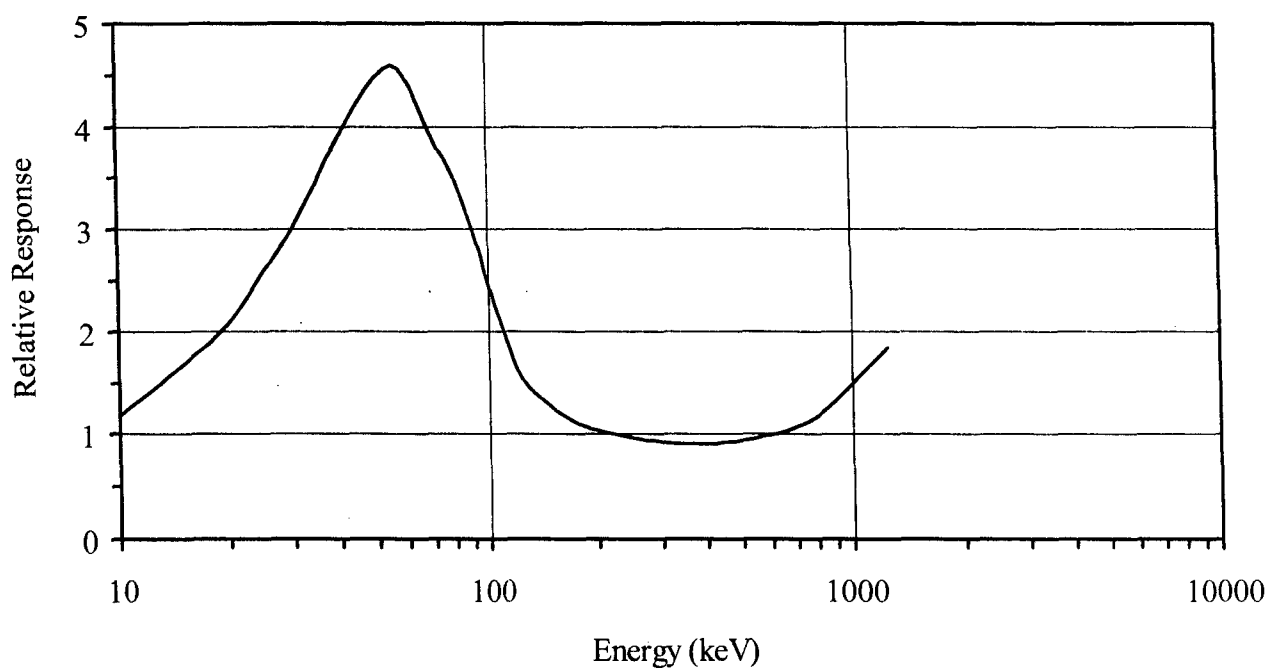


Figure A-6. Relative Energy Response of Victoreen Model 489-110 (Cardinal Health 2003).

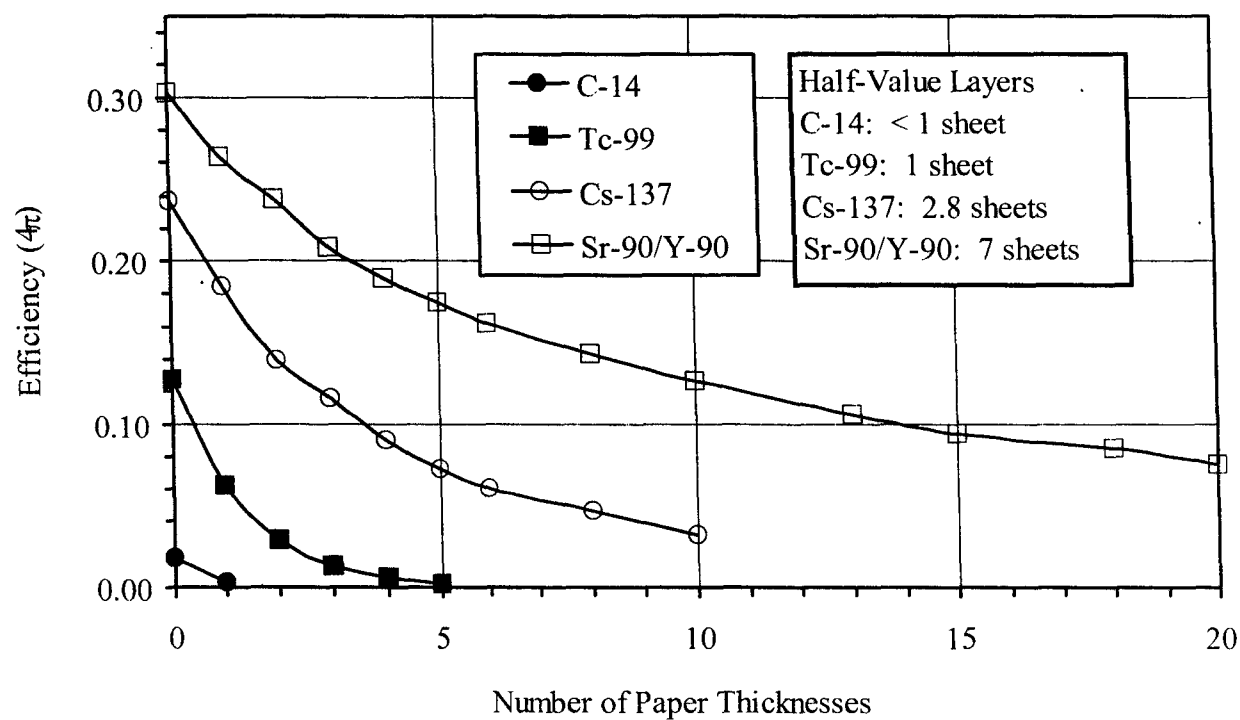
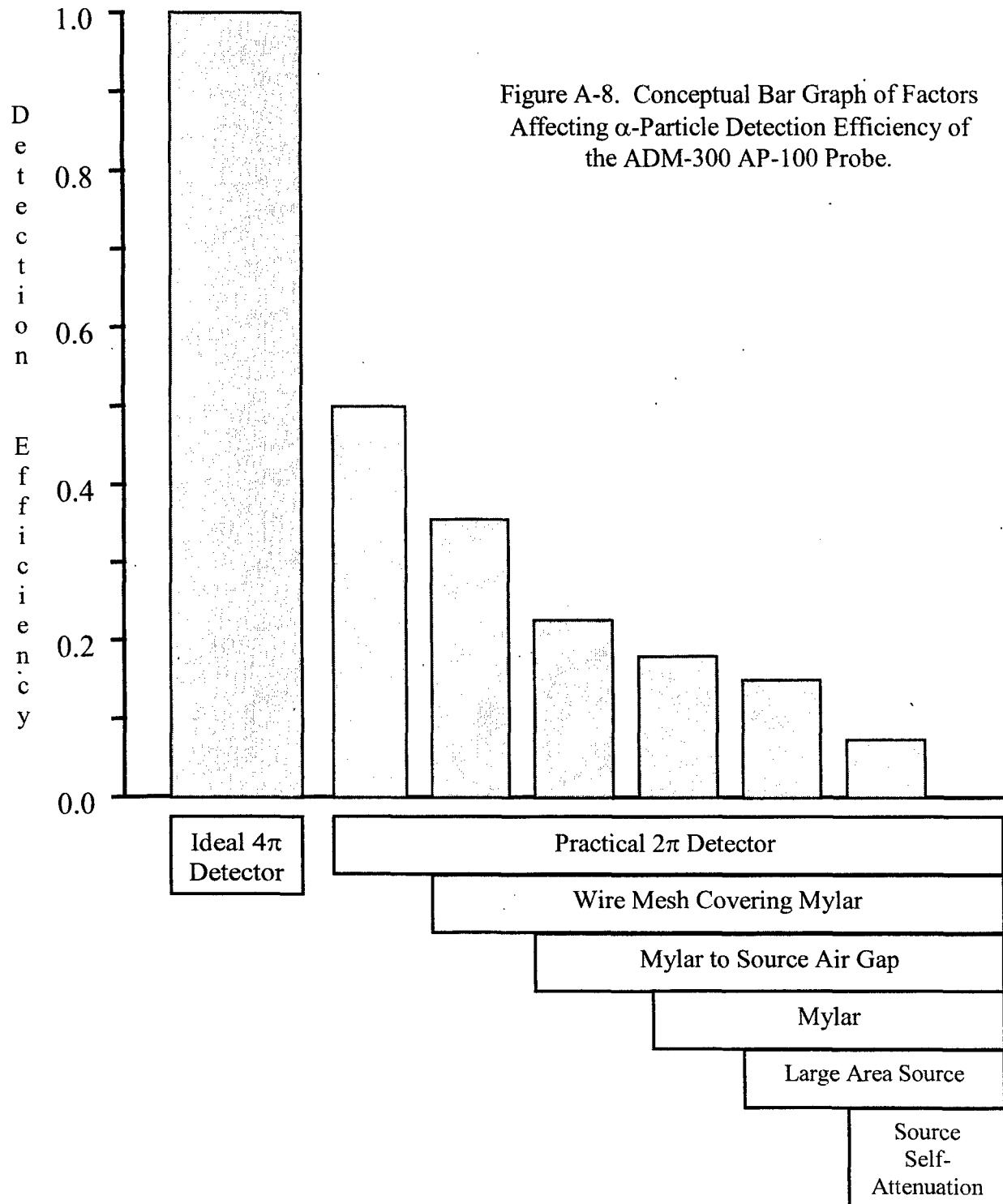


Figure A-7. Measured Detection Efficiency of Four  $\beta$ -Particle Emitters (Small Plated Sources) vs. Varying Thickness of Post-it<sup>®</sup> Paper with Ludlum 43-93 Probe [<sup>®</sup>Trademark of 3M].



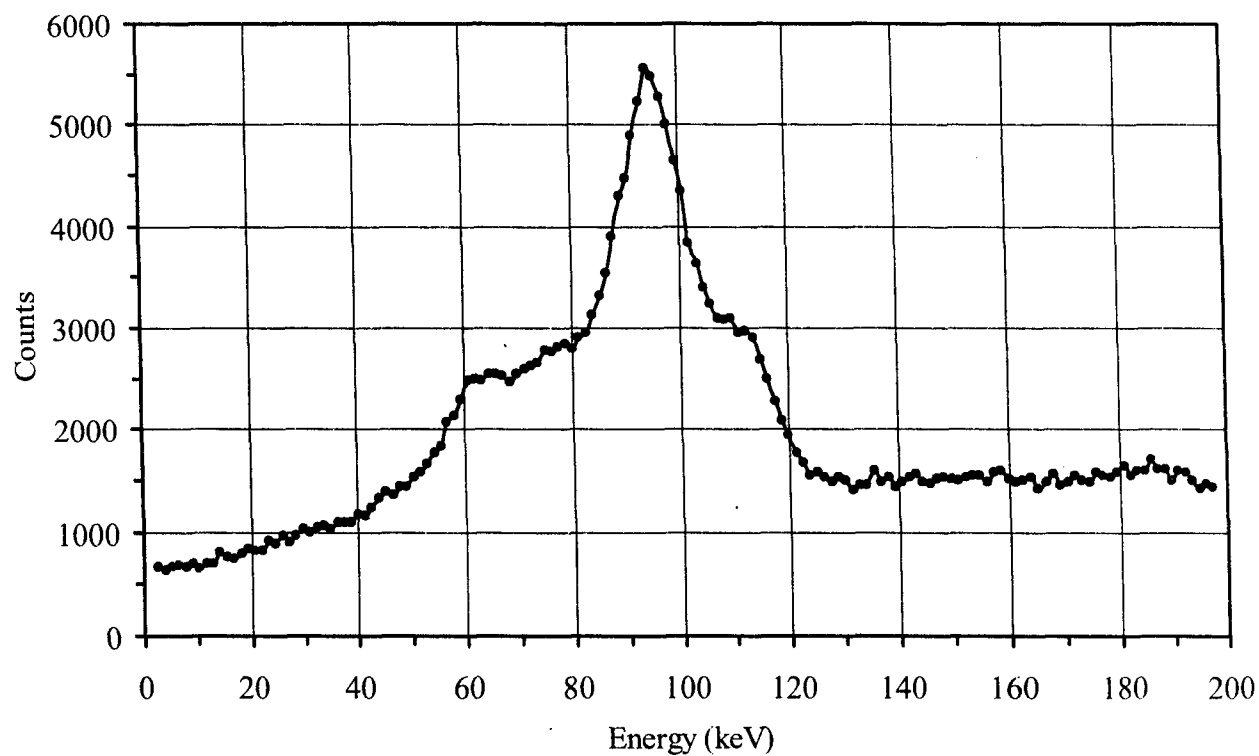


Figure A-9. Photon Emission Spectrum from DU Collected on a SPA-3 NaI(Tl).

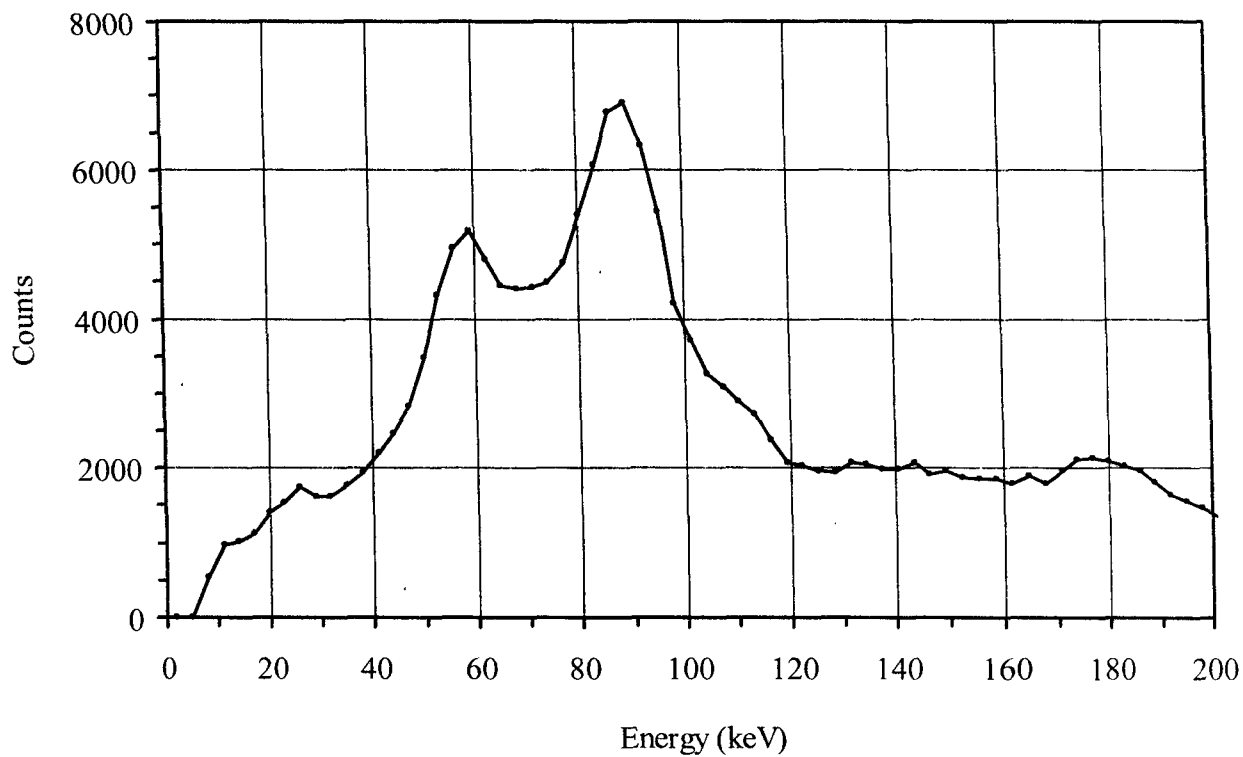


Figure A-10. Photon Emission Spectrum from DU in Soil Collected on a Canberra INSPECTOR 1.5 x 1.5 inch NaI(Tl).

## **Appendix B**

### **Surveys**

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TABLE B-1. Leak Test Procedural Checklist (Adapted from Mays 2004).

Step	Action	Check
1	Assemble the following items: a. AF Form 495 (one swipe envelope for each source) b. Swipe paper (NSN 6640-00-836-6870) c. Disposable gloves d. ADM-300 w/AP-100 and/or BP-100 (or equivalent instrument) e. Sealable plastic bag	
2	Record appropriate information on the AF Form 495 (see next page)	
3	Monitor the swipe prior to leak testing to establish background (note the count rate)	
4	Don gloves	
5	Remove sources from storage or access source location	
6	Mark the side of the swipe that will make contact with the source surface with an "x"	
7	Applying moderate pressure, wipe the source with the swipe	
8	Monitor the swipe with the instrument (note the count rate – this will be the gross count rate)	
9	Calculate the net count rate (net = gross – background) and contaminant activity (net count rate/efficiency)	
10	Compare to contaminant activity to acceptable removable activity (typically 0.005 $\mu\text{Ci}$ for NRC licensed material)	
11	If below acceptable level, assume source has good integrity and is not leaking, if over limit, follow conditions of AF RAM Permit	
12	Place swipe in AF Form 495.	
13	Remove gloves and place in plastic bag for storage as potential radioactive waste. (The gloves may be disposed in ordinary trash after acceptable negative test results are received.)	
14	Seal the envelope with tape. <b>DO NOT LICK!</b>	
15	Monitor the envelope and your hands. The exterior of the envelope shall not exceed 0.5 mrem/hr on the surface to be delivered by U.S. Mail Service.	
16	Place AF Form 495 in a larger envelope and mail to AFIOH/SDR.	
17	If you believe that you have a leaking source, notify AFIOH/SDR that a swipe with <u>potentially high levels of contamination</u> is being forwarded for analysis. In these cases, AFIOH can arrange for priority analysis, and telephonic or E-mail reporting.	

Portable Instrument		Serial Number	
External Probe		Serial Number	
Calibration Date		Background Count Rate	cpm
Gross Count Rate		Net Count Rate	cpm
Detector Efficiency		Activity = $\frac{\text{Net Count Rate}}{\text{Efficiency}}$	dpm
Divide Activity (dpm) by $2.22 \times 10^6$ for $\mu\text{Ci}$ units		Activity	$\mu\text{Ci}$

**List B-1. Instructions for Completion of AF Form 495  
Swipe Container (Adapted from Mays 2004).**

**Identification information**

**a. NAME AND ADDRESS OF SUBMITTING ACTIVITY** – Enter the organization and office symbol of the owning organization. This is where the analysis report will be mailed.

**b. NAME AND TELEPHONE NUMBER OF PERSON PERFORMING TEST** – Self-explanatory.

**c. RADIONUCLIDE OR TYPE OF RADIATION** – Enter the radionuclide appropriate to the instrument swiped or suspected contaminant on the surface being swiped.

**d. BASE SAMPLE NUMBER** – This is an eight-digit number starting with “WW” (represents swipes) followed by two-digit calendar year, and last four digits identify the locally assigned sequential number. The sequential number starts over each calendar year.

SWIPE CONTAINER			
NAME AND ADDRESS OF SUBMITTING ACTIVITY			DATE SUBMITTED
			RADIAC READING
NAME AND TELEPHONE NUMBER OF PERSON PERFORMING TEST			AREA SWIPED (SQ(M))
RADIONUCLIDE OR TYPE OF RADIATION		SOURCE CODE	
BASE SAMPLE NUMBER		SERIAL NUMBER OF SOURCE	
DATE RECEIVED	BASE CODE		USAF OEHL NUMBER
SEND TO: AFIOH/SDR 2350 Gillingham Drive Brooks City-Base TX 78235-5103			

**AF Form 495, Jul 87**

PREVIOUS EDITION WILL BE USED

**e. DATE SUBMITTED** – Self-explanatory.

**f. RADIAC READING** – Record the actual net reading of the survey instrument (cpm).

g. **AREA SWIPED** – Leave blank for leak tests, but for measurements of fixed area place in units of  $\text{cm}^2$  or  $\text{m}^2$ .

h. **SOURCE CODE** – Leave blank.

i. **SERIAL NUMBER OF SOURCE** – Enter the serial number of the source being swiped. This will allow AFIOH to add this number to the permanent database and analysis report.

j. **BASE CODE** – This is the code assigned by AFIOH. If you are unsure of this number, contact AFIOH.

k. **SEND TO** – The address on older forms is outdated. The proper current address is listed on the example form.

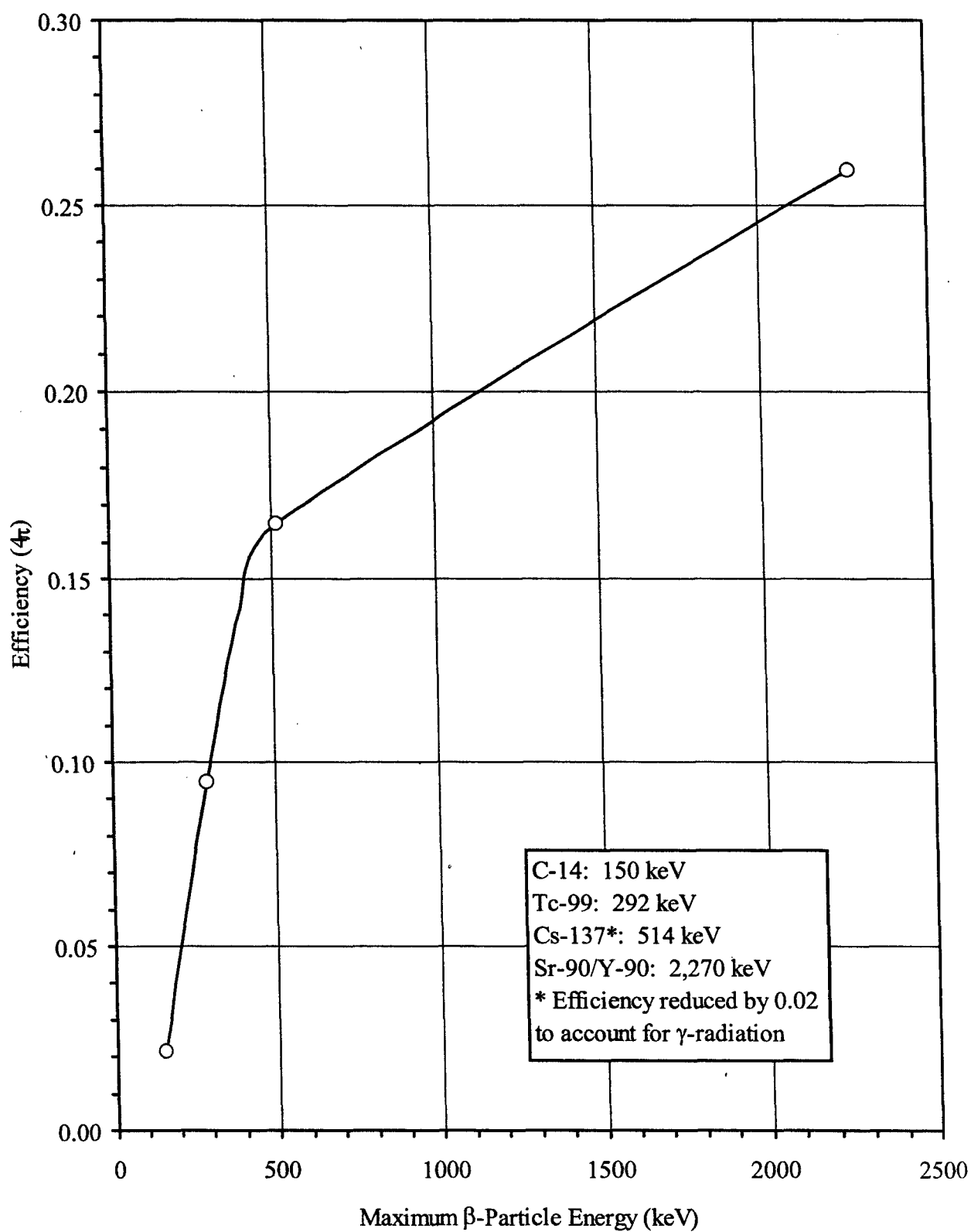


Figure B-1. Detection Efficiency of ADM-300 with BP-100 Pancake G-M from Figure 6-9.

TABLE B-2. Airborne Particle Retention (APR) and  $\alpha$ -Particle Self-Absorption Correction Factors for Various Filters (OEHL 1983).

Filter Type	Airborne Particle Retention (APR)						$\alpha$ -Particle Correction Factor
	Particle Diameter ( $\mu\text{m}$ )						
	< 0.4	0.4 – 0.6	0.6 – 0.8	0.8 – 1.0	1.0 – 2.0	> 2.0	
Whatman 41	0.23	0.28	0.64	0.74	0.70	100	0.55
Whatman 4	0.23	0.32	0.38	0.79	0.74	100	NL
MSA Type S	0.48	0.47	0.77	0.92	0.94	100	NL
H-70 (18 mil)	0.993						0.4
CWS-5	0.82						NL
CWS-6	0.999						NL
Glass Fiber	0.999						0.2
Millipore	0.999						1.0

NL = Not Listed

TABLE B-3. Volumetric Concentration Conversion Factors.

Multiple # of:	by	to obtain # of
dpm/ft <sup>3</sup>	$1.6 \times 10^{-11}$	$\mu\text{Ci}/\text{cm}^3$ ( $\mu\text{Ci}/\text{ml}$ )
dpm/ft <sup>3</sup>	$1.6 \times 10^{-5}$	$\mu\text{Ci}/\text{m}^3$
dpm/ft <sup>3</sup>	$5.9 \times 10^5$	$\mu\text{Bq}/\text{m}^3$
dpm/ft <sup>3</sup>	35	dpm/m <sup>3</sup>
dpm/ft <sup>3</sup>	$3.5 \times 10^{-5}$	dpm/cm <sup>3</sup>
dpm/ft <sup>3</sup>	$4.5 \times 10^{-7}$	$\mu\text{Ci}/\text{ft}^3$

TABLE B-4. Recommended Respiratory Protection Levels for Emergency Workers as a Function of Airborne Contamination [Table C5.T1, DoD 3150.8-M (DoD 1999)].

Airborne $\alpha$ -Radiation Activity Above Background	Respiratory Protection
Below 100 dpm/m <sup>3</sup>	No respiratory protection needed.
100 – 10,000 dpm/m <sup>3</sup>	Full-face respiratory protection required.
Above 10,000 dpm/m <sup>3</sup>	Pressure demand SCBA or limited entry restricted to essential personnel wearing full-face respiratory protection.

TABLE B-5. Shipment Quality Assurance Checklist (Mays 2004).



**WPAFB RADIATION SAFETY OFFICE**  
**SHIPMENT QUALITY ASSURANCE CHECKLIST**  
 Excepted Package



July 2004

Date: \_\_\_\_\_ Shipper: \_\_\_\_\_ Destination: \_\_\_\_\_

Item Description	Radionuclide	Activity Each	Number of Items	Total Activity

Instrument Used: Mfg: \_\_\_\_\_ Model: \_\_\_\_\_ S/N: \_\_\_\_\_ Cal Date: \_\_\_\_\_

Person Completing Checklist: \_\_\_\_\_ Signature: \_\_\_\_\_

**EXCEPTED PACKAGE SHIPMENT**

Yes No N/A

- ☐ ☐ ☐ 1. For LIMITED QUANTITY ONLY, outside of the inner package or outside of package itself bears the marking "Radioactive". [173.421(a)(4)]
- ☐ ☐ ☐ 2. For INSTRUMENTS AND ARTICLES ONLY, the radiation level at 10 cm from any point on the external surface of any unpackaged instrument or article does not exceed 10 mrem/hr. [173.424(b)]
- ☐ ☐ ☐ 3. For INSTRUMENTS AND ARTICLES ONLY, the active material is completely enclosed by non-active components (a device performing the sole function of containing radioactive material shall not be considered to be an instrument or manufactured article). [173.424(e)]
- ☐ ☐ 4. Package meets general design requirements (see definitions). [173.421(a)(1) or 173.424(a)]
- ☐ ☐ 5. Package contains less than 15 grams of U-235. [173.421(a)(5) or 173.424(b)]
- ☐ ☐ 6. Package less than §173.425, Table 4 (A<sub>1</sub>/A<sub>2</sub> Quantity Limits are found in §173.435). [173.421(a) or 173.424(b)&(c)]
- a. LIMITED QUANTITY: (see back for limits)
- Package limit: \_\_\_\_\_ Actual package activity: \_\_\_\_\_
- b. INSTRUMENT or ARTICLE: (see back for limits)
- Maximum package limit: \_\_\_\_\_ Actual package activity: \_\_\_\_\_
- Maximum article activity limit: \_\_\_\_\_ Actual maximum article activity: \_\_\_\_\_
- ☐ ☐ 7. Radiation level at any point on the external surface of package less than or equal to 0.5 mrem/hr. [173.421(a)(2) or 173.424(f)]
- ☐ ☐ 8. Removable surface contamination less than 2.2 dpm/cm<sup>2</sup> (alpha) or 22 dpm/cm<sup>2</sup> (beta/gamma). [173.421(a)(3) or 173.424(g)]
- ☐ ☐ 9. The outside of the package marked with the four digit UN identification number (i.e. UN2910 (LQ) or UN2911 (I&A)). [173.422(a)]
- ☐ ☐ 10. Full name and address of the shipper and consignee. [ATA 10.7.1.3.2]
- ☐ ☐ 11. Permissible gross weight marked on package, if exceeds 50 kg (110lb) [ATA 10.7.1.3.2]

**IMPORTANT:** If you checked "no" to any item above, contact WPAFB Radiation Safety Office for further instruction.

COMMENTS:

TABLE B-5. Shipment Quality Assurance Checklist (continued) (Mays 2004).

Wright-Patterson AFB Radiation Safety Office

ACTIVITY LIMITS

INSTRUMENTS & ARTICLES and LIMITED QUANTITY

(49 CFR 173.425)

Radionuclide	NORMAL FORM			SPECIAL FORM			Exempt Limit (μCi)	Exempt Concentration (Ci/gm)
	Instrument & Articles		Limited Quantity	Instrument & Articles		Limited Quantity		
	Instrument Limit	Package Limit		Instrument Limit	Package Limit			
Americium 241	270 μCi	27 mCi	27 μCi	27 Ci	270 Ci	270 mCi	0.27	2.7x10 <sup>-11</sup>
Cadmium 109	540 mCi	54 Ci	54 mCi	8.1 Ci	810 Ci	810 mCi	27	2.7x10 <sup>-6</sup>
Cobalt 57	27 Ci	270 Ci	270 mCi	27 Ci	270 Ci	270 mCi	27	2.7x10 <sup>-6</sup>
Cobalt 60	110 mCi	11 Ci	11 mCi	110 mCi	11 Ci	11 mCi	27	2.7x10 <sup>-6</sup>
Chromium 51	8.1 Ci	810 Ci	810 mCi	8.1 Ci	810 Ci	810 mCi	270	2.7x10 <sup>-6</sup>
Cesium 137	160 mCi	16 Ci	16 mCi	540 mCi	54 Ci	54 mCi	0.27	2.7x10 <sup>-10</sup>
Iodine 125	810 mCi	81 Ci	81 mCi	54 Ci	540 Ci	540 mCi	27	2.7x10 <sup>-6</sup>
Iron 55	11 Ci	1100 Ci	1.1 Ci	11 Ci	1100 Ci	1.1 Ci	27	2.7x10 <sup>-6</sup>
Krypton 85	270 mCi	27 Ci	270 mCi	270 mCi	27 Ci	270 mCi	0.27	2.7x10 <sup>-6</sup>
Nickel 63	8.1 Ci	810 Ci	810 mCi	11 Ci	1100 Ci	1.1 Ci	2700	2.7x10 <sup>-6</sup>
Plutonium 239	270 μCi	27 mCi	27 μCi	27 Ci	270 Ci	270 mCi	0.27	2.7x10 <sup>-11</sup>
Polonium 210	54 mCi	540 mCi	540 μCi	11 Ci	1100 Ci	1.1 Ci	0.27	2.7x10 <sup>-10</sup>
Promethium 147	540 mCi	54 Ci	54 mCi	11 Ci	1100 Ci	1.1 Ci	270	2x10 <sup>-7</sup>
Radium 226	810 μCi	81 mCi	81 μCi	54 mCi	54 Ci	54 mCi	0.27	2.7x10 <sup>-10</sup>
Tritium <sup>1</sup>	22 Ci	220 Ci	22 Ci	n/a	n/a	n/a	27000	2.7x10 <sup>-5</sup>
Uranium (depleted)	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited	2.7 x10 <sup>-10</sup>	2.7 x10 <sup>-11</sup>

**NOTES:**

<sup>1</sup> Tritium values also apply to deuterium in deuterated materials and will remain in force on total content.

## NOTES:

<sup>1</sup> These values also apply to tritium as provided in 49 CFR 173.425 and 173.426 on this carrier.

## DEFINITIONS

## General Design Requirements:

1. Easily handled and secured in or on conveyance.
2. If lifting attachment, designed with safety factor.
3. External surfaces free from protruding features and easily deconned.
4. Outer layer will avoid water collection.
5. Each feature added does not reduce safety of package.
6. Withstands conditions of normal transport including closing devices.
7. Materials physically and chemically compatible.
8. Values protected against unauthorized operation.
9. For transport by air - a) temp. of surface will not exceed 50°C with ambient temp at 38°C, b) integrity maintained if ambient temp. at -40°C to 55°C, and c) liquids will not leak at pressure differential of not less than 95 kPa (13.8 lb/in<sup>2</sup>).

**Radioactive Instrument and article:** Any manufactured instrument and article such as an instrument, clock, electronic tube or apparatus, or similar instrument and article have Class 7 (radioactive) material in gaseous or non-dispersible solid form as a component part.

**Normal form:** Radioactive material, which has not been demonstrated to qualify as "special form Class 7 (radioactive) material."

**Special form:** Radioactive material which satisfies: 1) single solid piece or in a sealed capsule that can only be opened by destroying capsule; 2) piece or capsule has at least one dimension not less than 5 mm; and 3) it satisfies test requirements of 49 CFR 173.469.

**Contamination Limit:** The amount of radioactivity measured on any single wiping material, divided by the surface area wiped and divided by the efficiency of the wipe procedure (may be assumed to be 0.10), may not exceed contamination limits.

**Exempt Limit Concentration:** Used to determine whether a given radioactive material is sufficiently radioactive to be subject to DOT HMR.

## NON-FIXED EXTERNAL RADIOACTIVE CONTAMINATION-WIPE LIMITS

(Averaged over 300 cm<sup>2</sup>)  
(49 CFR 173.443)

Contaminant	Maximum permissible limits		
	Bq/cm <sup>2</sup>	μCi/cm <sup>2</sup>	dpm/cm <sup>2</sup>
Beta and gamma emitters and low toxicity alpha emitters	4	10 <sup>-4</sup>	220
All other alpha emitting radionuclides	0.4	10 <sup>-5</sup>	22

## Swipe Evaluation (ADM-300):

$$\frac{Bq}{cm^2} = \frac{cpm (net)}{0.5 \times E_p \times 60 \frac{sec}{min} \times A (cm^2) \times 0.1}$$

$E_p$  = Probe Efficiency (AP-100 = 0.3 for <sup>226</sup>Pu; BP-100 = 0.45 for <sup>235</sup>Sr)

$A$  = Area Swiped (300 cm<sup>2</sup>)

0.5 = 2  $\pi$  to 4  $\pi$  geometry conversion

cpm<sub>net</sub> = Background subtracted from gross count

1 Bq = 1 dps or 60 dpm

0.1 = swipe efficiency

## EXAMPLE:

$$\frac{Bq}{cm^2} = \frac{100 \text{ cpm}}{0.5 \times 0.3 \times 60 \frac{sec}{min} \times 300 \text{ cm}^2 \times 0.1}$$

$$= 0.37 \text{ Bq/cm}^2$$

## List B-2. Procedure for Safely Opening Packages Containing RAM (Adapted from NRC 1999).

1. Wear gloves to prevent hand contamination.
2. Visually inspect the package for any sign of damage (e.g. crushed, punctured). If damage is noted, stop and notify the RSO.
3. Check DOT White I, Yellow II, and Yellow III label for packing slip for activity of contents, in the case that the RAM will cause an exceedence in an AF permit authorization. [Note: Excepted packages will not have DOT labeling]. If an exceedence could occur, contact AFMSA/SGPR for guidance.
4. Monitor the external surface of a labeled package according to DOT limits: Table 5-8 of this report for removable contamination and Table 5-7 of this report for dose-equivalent rate. If levels exceed DOT limits stop and notify the RSO.
5. Open the outer package (following supplier's directions if provided) and remove packing slip. Open inner package to verify contents (compare requisition, packing slip and label on the bottle or other container). Check integrity of the final source container (e.g. inspecting for breakage of seals or vials, loss of liquid, discoloration of packaging material, high count rate on field-portable instrument measurement of swipe sample). Check again that the shipment dose not exceed AF permit possession limits (if AF-permitted). If you find anything, other than expected, stop and notify the RSO.
6. Survey the packing material and packages for contamination before discarding or releasing for re-use. If contamination is found, treat as radioactive waste. [Note: For short-lived isotope (i.e. primary those used in medicine) packages may be released to regular trash or re-use after sufficient decay]. If no contamination is found, obliterate the radiation labels prior to discarding in the regular trash or storage (subsequent re-use).
7. Maintain the records of receipt, package survey (if labeled White I, Yellow II, or Yellow III), and swipe test results.
8. Notify the final carrier and the AF Radioisotope Committee (RIC), AFMSA/SGPR, when removable contamination exceeds the limits of 10 CFR 71.87(i) or external radiation levels exceed the limits of 10 CFR 71.47. 10 CFR 71.87(i) refers to DOT-specified removable contamination limits (Table 5-8 of this report). 10 CFR 71.47 refers to the Yellow III limits: 200 mrem/hr at any point on the external surface of package and a TI of 10.
9. Recommendations to RSOs with damaged packages and/or packages that:
  - a. exceed DOT contamination limits,
  - b. DOT external radiation standards, or
  - c. have contaminated sources.

Contaminated packages or contents should be placed in sealable plastic bags to reduce the potential for cross-contamination. The same protection should be afforded to damaged packages until they



are confirmed to be contamination free. Packages or sources with high external exposure rates should be placed in locations providing shielding and/or remoteness to personnel/public. The cosignee should be contacted to determine how internal contents were packed or other information that would aid in safely opening the package. AFIOH/SDR should be contacted for technical guidance.

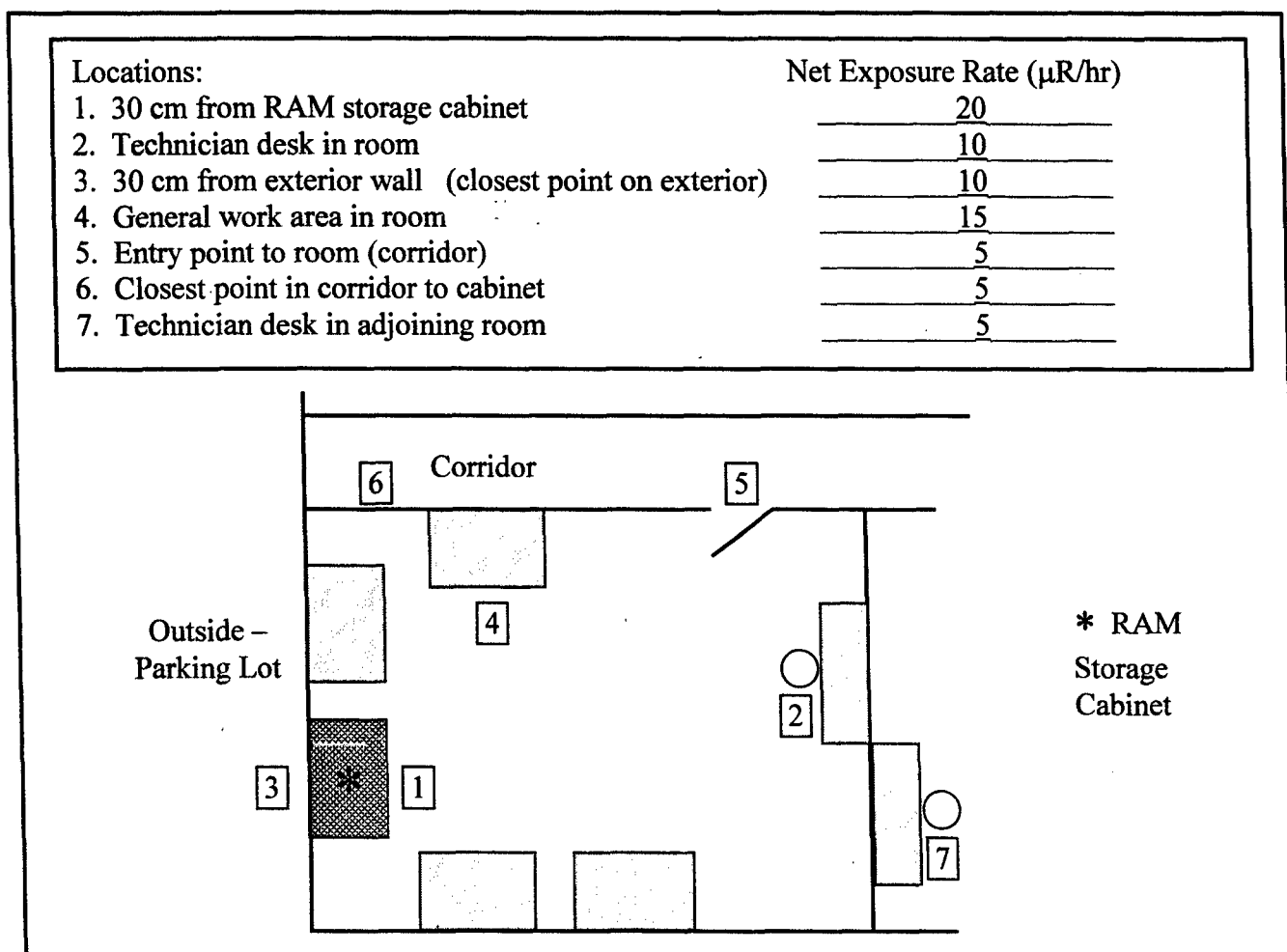
**Radioactive Material Storage Area Survey for Materials under  
USAF Permit Number NM-XXXXXX-XX/XX**

Survey Location: In and Vicinity of Room XYZ, Building ABC, Best AFB NM  
Using Organization: XYZ AMDS/SGPB

Radioactive Material: Small Check Sources for ADM-300, NITON Gauge w/ Ni-62 & Am-241,  
M8A1/M43A1s w/ Am-241, ICAMS w/ Ni-63, and Compasses

Surveyed By: SrA John Snuffy, John B. Snuffy, Date: 19 Apr 05

Survey Instrument: ADM-300 (internal G-M) Calibrated: 05 Jan 05 Due: 04 Jan 06  
Serial Number: 00213 Background Exposure Rate: 15  $\mu$ R/hr



Page 1 of 2, XYZ AMDS/SGPB, Ltr 19 Apr 05

Figure B-2. Example RAM Storage Area - Survey Measurement Documentation.

**Radioactive Material Storage Area Survey for Materials under  
USAF Permit Number NM-XXXXXX-XX/XX (Continued)**

1. Summary of Operations in Room XYZ. Room XYZ is used by Bioenvironmental Engineering Services for the Storage and Maintenance of Equipment used for BES Operations. Among the items being stored in the room, one cabinet contain a variety of radioactive materials that are contained in devices, are check sources, or small generally-licensed source. An equipment technician works in the room and has a desk location. Adjacent to the room is a corridor, another room that contains desks for technicians, and two exterior walls, one of which has an adjacent automobile parking lot.

2. Occupational Exposure. The table below provides a summary of conservative exposures for the technician assigned for duties in the room and other technicians that use the room periodically and have a desk adjacent to the room. From the survey, no location had an accessible exposure rate above 2 mrem in any one hour and the projected annual dose-equivalent is below 100 mrem in a year (general public limit). Thus, the room is an unrestricted area with respect to radiation exposure. Personal dosimetry and other surveillance are not required.

Location	Technician Assigned to Room		Other Technicians	
	Fraction	Dose Equivalent (mrem)	Fraction	Dose Equivalent (mrem)
2	0.5	10		
4	0.25	7.5	0.1	3
6			0.5	5
Other	0.25	0	0.4	0
Total	1.0	17.5	1.0	8

3. General Public Exposure. The highest accessible exposure rate to members of the general public is at location 3, where the projected annual dose-equivalent level is 29 mrem (365 days \* 8 hrs/day \* 10  $\mu$ R/hr). The exposure rate at this location is below 2 mrem in any one hour and the projected annual exposure is below 100 mrem/yr, the annual limit for members of the public.

TABLE B-6. Non-Destructive Inspection Radiation Safety Checklist.

Criterion	Yes	No	N/A
<b>Radiation Monitoring Equipment</b>			
1. Appropriate ion chamber or energy-compensated G-M (ADM-300) for monitoring environment?			
2. Monitoring equipment within calibration period?			
3. RFR interference? If so, consider RF shielded ion chamber.			
4. Personal TLD issued to all radiographers?			
5. Real-time dosimeter (pocket ionization chamber or electronic personal dosimeter) for radiographers?			
6. Real-time dosimeters within calibration period? (annual calibration)			
7. Proper central storage location for TLDs and control, and pocket ionization chambers?			
8. Real-time dosimeter readings recorded daily (unshielded operations) ?			
9. EPD audible alarm checked prior to each work day?			
10. EPD audible alarm set at dose rate < 500 mR/hr?			
11. Real-time dosimeter log maintained for three (3) years?			
<b>Operating Instructions</b>			
12. Operating instructions developed?			
a. Ensure personnel are removed during exposures?			
b. Verification of proper operation of interlocks, warning lights, etc. every day of use?			
c. Qualified operator at control console during all exposures?			
d. Minimum of two (2) operational ion chambers (or equivalent) available during operations?			
e. Emergency procedures part of OI's?			
f. OI's specific to shielded (enclosed)/unshielded operations?			
g. Survey meter used during entries into controlled areas after exposures?			
<b>Restricted Areas</b>			
13. Restricted areas (> 2 mrem in any one (1) hour) established?			
14. Radiation areas (> 5 mrem in any one (1) hour) established?			
15. High radiation areas (> 100 mrem in any one (1) hour) established ?			
16. Very high radiation areas (> 500 rad in any one (1) hour) established ?			
17. Warning signs posted for individual areas?			
<b>Engineering Controls (Shielded Operations)</b>			
18. Visible and audible warnings that x-ray machine is operating?			
19. Visible and audible warnings tied to interlock system?			
20. Visible and audible warning operate prior to exposure?			
21. Access interlock system that interrupts power to x-ray console if interlock broken?			
22. Emergency shut-off switch within the enclosure that is readily visible?			

TABLE B-6. Non-Destructive Inspection Radiation Safety Checklist (continued).

Criterion	Yes	No	N/A
<b>Engineering Controls (Unshielded Operations)</b>			
23. Visible warning beacon indicating that x-ray machine is operating?			
24. Emergency shut-off switch located between the console and warning beacon?			
<b>Administrative Controls (Unshielded Operations)</b>			
25. Restricted areas roped off to control access during irradiation operations?			
26. Safety monitors designated to control restricted areas where other controls are not practical?			
<b>Exposure Evaluations</b>			
27. Radiation exposure potential evaluated for unshielded and shielded facilities based on measurements or calculations?			
28. Current measurements to account for changes in shielding, workload, equipment, etc.?			
29. Pocket ionization chamber, TLD, and electronic personal dosimeters evaluated for compliance with ALARA and AFI 48-148 exposure limits?			
30. Workers have access to dosimetry results?			
<b>Training</b>			
31. Workers have appropriate initial training for working with x-rays according to T.O. 33B-1-1?			
32. Radiation Safety Monitors Assistants have training as dictated by BES?			
33. Workers have annual refresher training on radiation safety?			